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Ontario Geological Survey
Open File Report 6032

Summary of Field Work and Other Activities 2000

2000

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ERRATUM

Open File Report 6032—Article 14

Summary of Field Work and Other Activities 2000

In Article 14, "Precambrian Features under the James Bay and Hudson Bay Lowlands" in *Summary of Field Work and Other Activities 2000,* two text labels in the top left part of Figure 14.1 were inadvertently switched. The upper text label should read "On Strike with Pikwitonei Domain (Manitoba)", and the lower one, "Older Crustal Component on Strike with Gods Lake Domain (Manitoba)".

If you wish to view and print a corrected version of this page, this article, along with the entire *Summary of Field Work 2000* volume, is available on the Mines and Minerals Web site at: http://www.gov.on.ca/MNDM/MINES/PUB/mmdpube.htm

We regret any inconvenience this error may have caused.

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6032

Summary of Field Work and Other Activities 2000

edited by

J.A. Ayer, C.L. Baker, R.I. Kelly, J.R. Parker, G.M. Stott and P.C. Thurston

2000

Parts of this publication may be quoted if credit is given. It is recommended that reference to articles in this publication be made in the following form:

Ayer, J.A. 2000. The Abitibi greenstone belt: a program overview; *in* Summary of Field Work and Other Activities 2000, Ontario Geological Survey, Open File Report 6032, p.3.1 to 3.4.

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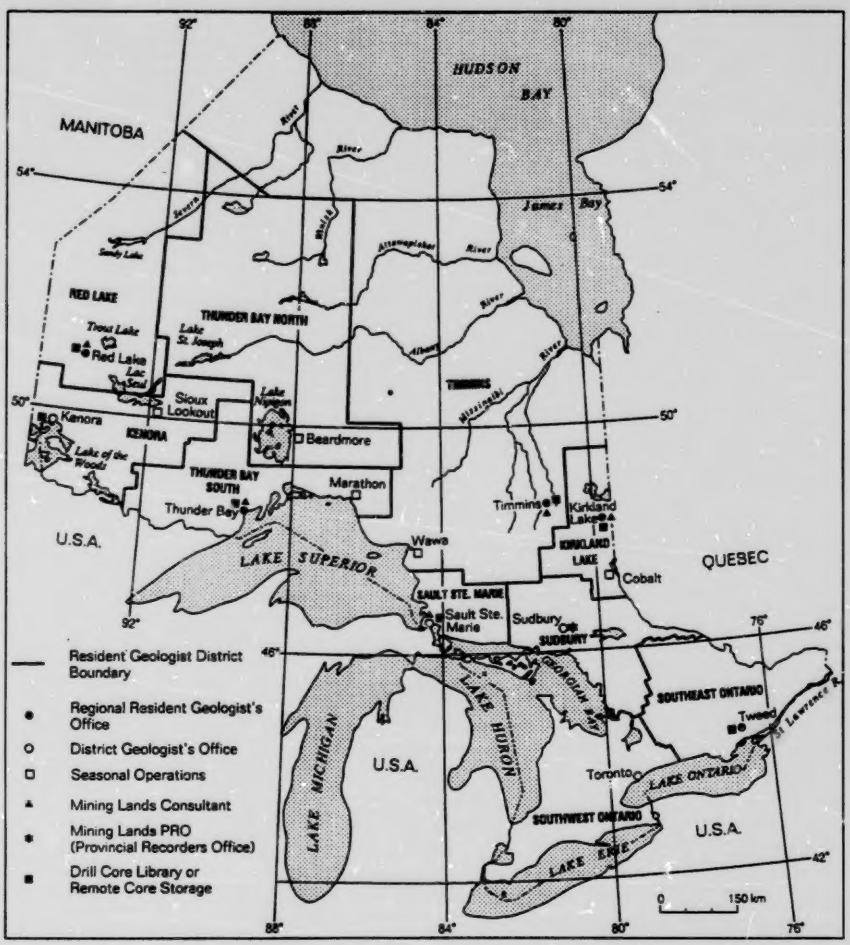

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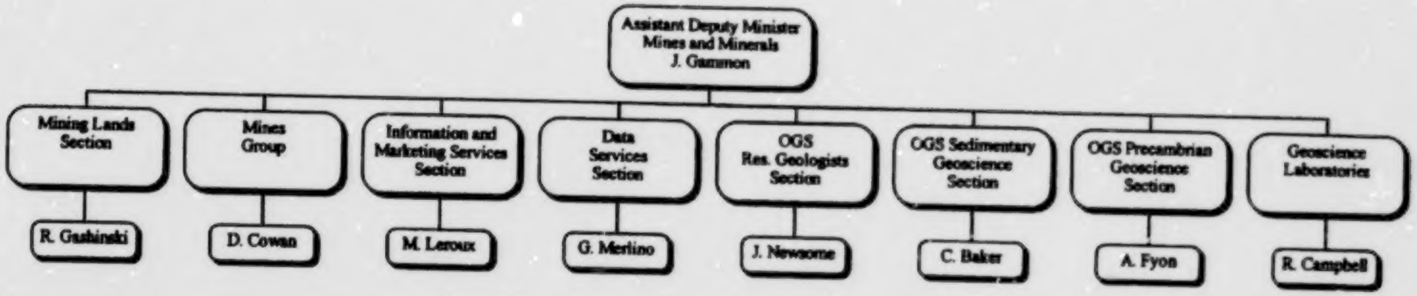


Contents

Precambrian Geoscience Section

1. Precambrian Geoscience Section – Program Overview *J.A. Fyon*
2. Precambrian Initiatives and Regional Controls on Mineralization *P.C. Thurston*

Abitibi

3. The Abitibi Greenstone Belt: A Program Overview *J.A. Ayer*
4. Project Unit 00-011. New Geological Mapping and Compilation in the Timmins West Area – Bristol and Ogden Townships *C. Vaillancourt*
5. Project Unit 97-013. Continuing Structural Investigations of Gold Mineralization along the Porcupine–Destor Deformation Zone in the Harker–Holloway Gold Camp, Abitibi Greenstone Belt *B. Luinstra*
6. Project Unit 98-15. Lithogeochemistry of the Shining Tree Area *H.S. Oliver, D.J. Hughes, R.P. Hall and G.W. Johns*
7. Project Unit 00-043. Geology, Volcanology, Lithogeochemistry and Alteration Associated with Volcanogenic Base Metal Mineralization in the Big Four Lake Area, Shining Tree, Abitibi Greenstone Belt, Ontario *G. Leblanc, G.W. Johns, J. Ayer and A.D. Fowler*
8. Project Unit 99-026. Petrogenesis of Syenitic Magmatism Associated with Gold Mineralization Along the Destor–Porcupine Fault Zone Near Matheson, Ontario *L. Pigeon, A.E. Lalonde and B. Berger*
9. Project Unit 00-042. Structural Study of the Kenogamissi Batholith and Surrounding Swayze/Abitibi Greenstone Belt *J.K. Becker and K. Benn*
10. Project Unit 99-020. Temporal and Spatial Variations in Komatiite Geochemistry in the Abitibi Greenstone Belt *R.A. Sproule, C.M. Lesher, J.A. Ayer and P.C. Thurston*
11. Project Unit 99-021. Physical Volcanology and Metallogenesis of Komatiites in the Abitibi Greenstone Belt, Superior Province, Canada *M. Houlé, C.M. Lesher, A.D. Fowler, R.A. Sproule, J.A. Ayer, H.L. Gibson and P.C. Thurston*
12. Project Unit 00-011. Structural Investigations of the Echo Bay and International Falcon Properties in Ogden Township *É. Dinel and K. Benn*

NATMAP

13. Project Unit 95-034. An Integrated View of Western Superior Crustal Evolution: Highlights of 2000 NATMAP Studies *J.A. Percival, A.H. Bailes, M.T. Corkery, B. Dubé, J.R. Harris, V. McNicoll, D. Panagapko, J.R. Parker, N. Rogers, M. Sanborn-Barrie, T. Skulski, D. Stone, G.M. Stott, P.C. Thurston, K.Y. Tomlinson, J.B. Whalen and M.D. Young*
14. Project Units 98-006 and 98-007. Precambrian Features Under the James Bay and Hudson Bay Lowlands *G.M. Stott and B.J. Berdusco*
15. Project Unit 95-15. Geology of the Blackbear, Yelling and Stull Lake Areas, Northern Superior Province, Ontario *D. Stone and J. Hallé*

16. Project Unit 95-14. Geology of the Petry River Area, South-Central Wabigoon Subprovince *D. Stone and J. Hallé*

17. Project Unit 00-08. Geology of the Heaven Lake Greenstone Belt, Central Wabigoon Subprovince *T.R. Hart and C.A. MacDonald*

18. Project Unit 00-08. Geology of the Lac des Iles Greenstone Belt, Central Wabigoon Subprovince *T.R. Hart and C.A. MacDonald*

19. Project Unit 00-012. Magnetic Susceptibility: Selected Applications to Geological Studies and Mapping *G.P. Beakhouse*

20. Project Unit 99-001. Precambrian Geology of the Wabigoon Area *G.P. Beakhouse*

21. Project Unit 99-022. The Entwine Lake Intrusion: A Neoarchean Cu-Ni-PGE Bearing Intermediate to Mafic Complex in the Western Wabigoon Subprovince, Northwestern Ontario *J. Arnold, G. Beakhouse and R. James*

22. Project Unit 98-002. Gold Mineralization and Wall Rock Alteration in the Red Lake Greenstone Belt: A Regional Perspective *J.R. Parker*

23. Project Unit 98-002. Nickel-Copper-Platinum Group Element Sulphide Mineralization in the Red Lake Greenstone Belt: A Preliminary Report *J.R. Parker*

24. Project Unit 98-016. Combined U-Pb Columbite and ^{40}Ar/^{39}Ar Mica Ages from Rare-Element Pegmatites, Superior Province of Northwestern Ontario *S.R. Smith, R.L. Romer, F.W. Breaks, S.P. Kelley and A.G. Tindle*

25. Project Unit 00-001. Structural Investigation of Mesothermal Gold Mineralization in the Beardmore–Geraldton Terrane *J.C. DeWolfe, B. Lafrance, and G.M. Stott*

26. Project Unit 99-011. Geochemistry of Hydrothermal Alteration and its Relation to Base-Metal Mineralization in the Marshall Lake Area, Northern Margin of the Onaman–Tashota Greenstone Belt *K.H. Straub*

Lithoprobe

27. Project Unit 99-025. Detailed Structural Studies in the Atikokan–Ignace area, Northwestern Ontario *W.M. Schwerdtner and S. Ahmad*

Southern Province

28. Project Unit 99-07, 95-31 and 94-07. Variation in Crustal Level and Large-Scale Tectonic Controls on Rare-Metal and Platinum-Group Element Mineralization in the Southern and Grenville Provinces *R.M. Easton*

29. Project Unit 99-019. Geology, Stratigraphy, Geochemistry, and Copper-Nickel-Platinum Group Element Mineralization in the River Valley Intrusion *J.L. Hrominchuk*

30. Project Unit 96-098. Geology of the Foy and Whistle–Parkin Offset Dikes of the Sudbury Structure, and Contact Metamorphism around the Sudbury Igneous Complex *J.G. Spray, M. Boast, A.J. Murphy, J.P. O'Connor, R.G. Scott and M. Tuchscherer*

Land Use Planning Initiatives

31. Project Unit 00-31. Provincially Significant Mineral Potential Maps – The Role of the Precambrian Geoscience Section *B. Berger and R. Debicki*

Sedimentary Geoscience Section

32. Aggregate Resources Inventory Program Summary *D. Rowell and G. Gao*

33. Project Unit 99-017. Quaternary Geology Mapping and Overburden Sampling, Schreiber Area, Northwestern Ontario *T.F. Morris*

34. Project Unit 00-037. Regional Modern Alluvium Sampling Survey of the Temagami-Marten River Area, Northeastern Ontario *S.E. Allan*

35. Project Unit 00-35. Drift Exploration for PGEs, Northwestern Ontario *C.A. Searcy*

36. Project Unit 00-35. Kabinakagami Lake Area High Density Regional Lake Sediment and Water Geochemical Survey, Northeastern Ontario *J.E. Jackson*

37. Project Unit 00-039. Savant Lake High Density Regional Lake Sediment and Water Geochemical Survey, Northwestern Ontario *D.F. Russell*

38. Project Unit 00-033. Satellite-Based Engineering Geology Terrain Studies for Ontario's Far-North *P.J. Barnett and V.H. Singhroy*

39. Project Unit 00-32. Shale Resources of the Queenston Formation *D.K. Armstrong*

Geoscience Program Initiatives

Operation Treasure Hunt (OTH)

40. Operation Treasure Hunt — Update *J.A. Fyon, C.L. Baker, G. Merlino, P.C. Thurston, R. Kelly, R. Dyer, F. Santaguida, R. Denomme, Z. Madon, S.W. Reford and L.L. Churchill*

41. Project Unit 99-302. Operation Treasure Hunt: Airborne Geophysical Projects *S.W. Reford, E. Mueller, Z. Madon and J.A. Fyon*

42. Project Unit 99-316. Bedrock Map Compilation, Northwestern Ontario; Operation Treasure Hunt *F. Santaguida*

43. Project Unit 00-303. Physical Rock Properties Study in the Matheson and Kirkland Lake Areas *S. Deschamps*

44. Project Unit 99-315. OTH Lake Sediment Geochemistry *R. Dyer*

45. Project Unit 00-305. OTH Indicator Mineral Surveys *R. Dyer*

46. Project Unit 00-306. OTH Aggregate and Industrial Mineral Surveys *R. Dyer*

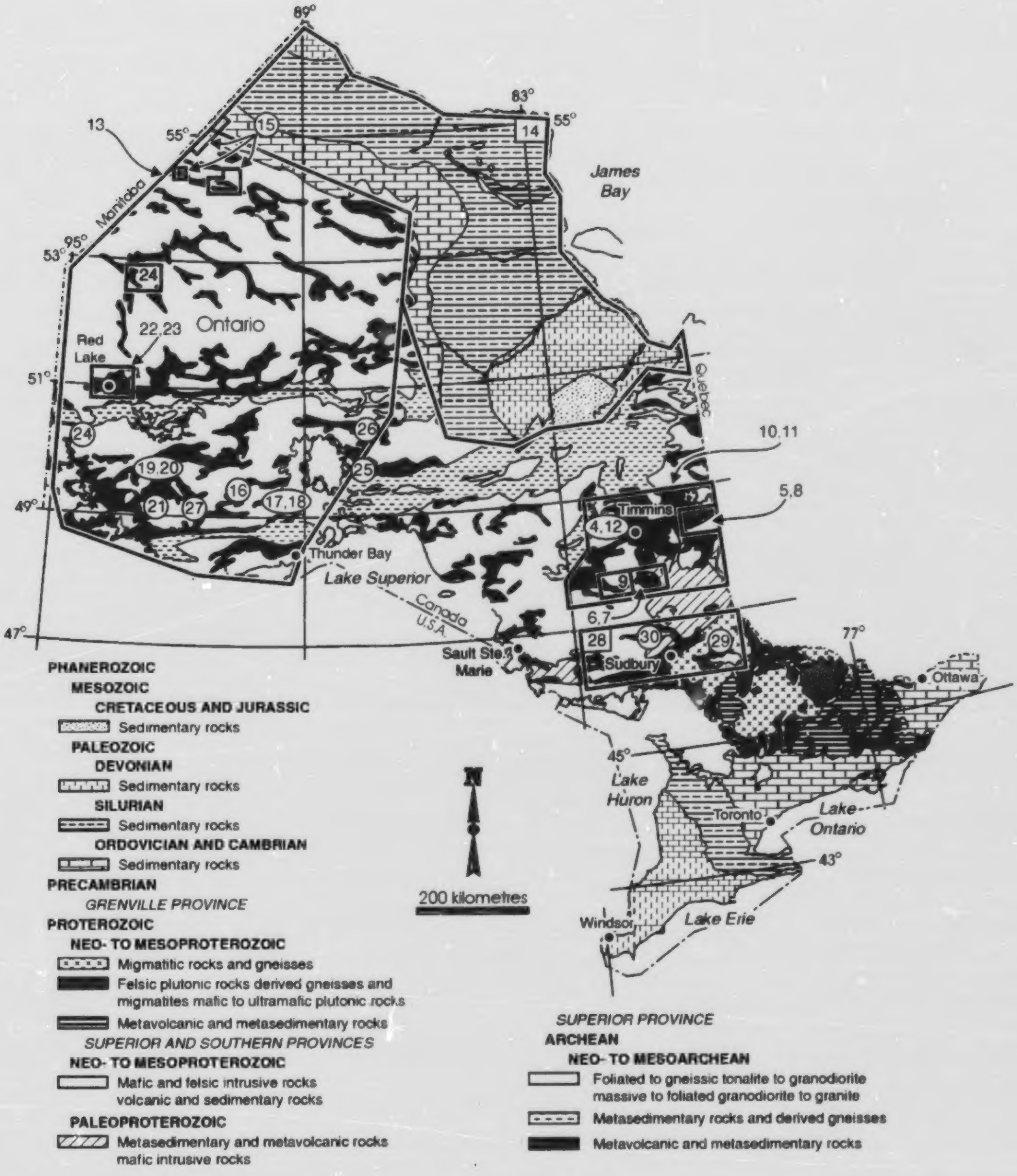
47. Project Unit 99-318. Thick Overburden Geochemistry – Methods and Case Studies *S.M. Hamilton and D.R. Cranston*

48. Project Unit 00-029. Preliminary Impact Analysis of Operation Treasure Hunt Surveys *L.L. Churchill, J. Roque, C.L. Baker and J.A. Fyon*

Index of Authors

Metric Conversion Table

Precambrian Geoscience Section



Locations of Precambrian Geoscience Section project areas. Numbers correspond to article numbers.

1. Precambrian Geoscience Section – Program Overview

J.A. Fyon[1]

[1] Precambrian Geoscience Section, Ontario Geological Survey

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GOAL AND RESPONSIBILITY OF THE PRECAMBRIAN GEOSCIENCE SECTION

The goal of Precambrian Geoscience Section (PGS) is to improve the understanding of the Precambrian geology of Ontario and mineral deposit settings and to convey this knowledge to clients through multi-year, multi-disciplinary studies to address critical geological problems, in key geographic areas.

PGS is responsible for:

- mapping of Ontario's Precambrian bedrock and understanding of their mineral deposit settings;
- regional gravity, magnetic and electromagnetic geophysical data and derivative products in support of the bedrock mapping program.

PROGRAM DIRECTION – STRATEGIC THRUSTS

Core Bedrock Mapping and Geophysics Program

The PGS program is organized into six strategic thrusts (Table 1.1):

- understand provincial-scale relationships and settings of potential diamond-bearing rocks, rare-metal and/or petalite-bearing pegmatites, and platinum-group mineralization
- understand the geology and metallogeny of high mineral potential areas (e.g., greenstone belts) in the Superior Province
- inventory key provincial-scale data sets relevant to mineral exploration
- understand the geology and metallogeny of high mineral potential areas in the Grenville and Southern provinces
- implement program support processes and instruments to address and refine the human resource strategy, digital data standards and program management practices
- provide liaison role, representation, or support on behalf of the Mines and Minerals Division, the OGS, and PGS on committees, boards, meetings, or program needs

These strategic thrusts are addressed through a series of initiatives, built upon one or more projects (Thurston, this volume). The purpose of the strategic thrusts is to focus the skilled staff and resources in key geological areas to address the bedrock and mineral deposit needs. The strategic thrusts may be area-specific or provincial in scope.

To complement existing PGS staff skills, part of the PGS program is delivered through collaborative projects, or "partnerships", with universities, other governments, and industry (Table 1.2).

Provincially Significant Mineral Potential Project

In the spring, approximately 6 PGS staff were assigned to prepare bedrock geology themes as part of the Provincially Significant Mineral Potential (PSMP) project. The staff assignment reflects the importance of this project to help ensure that technical data are available with which to make informed land-use decisions. Thurston (this volume) describes the PGS role in this project.

Mapping Productivity

Despite the re-assignment of mapping geologists to PSMP project, PGS field staff mapped 5934 km^2 at 1:50 000 scale or more detailed during the summer 2000.

PROJECT PLANNING, MANAGEMENT, AND CONSULTATION PROCESS

To plan and deliver approximately 85 active projects, delivered by core staff and in collaboration with our partners, project management is a "best practice" employed in the PGS program. Information required to describe projects, monitor and adjust progress, and assess their impact on the minerals industry is collected and analyzed to assess if program goals are met (e.g., Churchill and Fyon 1999).

To formulate and discuss project plans for summer of 2000 and to begin development of summer 2001 project plans, PGS staff were involved in several consultations:

1. December 1999: with representatives of most regional client associations and the Resident Geologist Program to determine their geoscience needs at a workshop in Sudbury
2. April 2000: with the OGS Technical Committee
3. March 2000: with subset of industry clients, Mineral Exploration Research Centre (Laurentian University), and representatives of the Resident Geologist Program and Precambrian Geoscience Section to design a platinum-palladium project for Operation Treasure Hunt
4. June 2000: with First Nation communities of Bearskin Lake, Sachigo Lake, Eabametoong Lake; due to a schedule conflict, there was no official meeting held with Sachigo community, although PGS staff did visit the community
5. January, April and September 2000: co-planning sessions with the Geological Survey of Canada.

ADD-ON PROGRAMS

PGS staff collaborate with other OGS staff to formulate and deliver two significant add-on geoscience programs.

Operation Treasure Hunt

Operation Treasure Hunt began in April 1999 to generate new exploration targets in industry priority areas, while contributing new geoscience information to enhance the understanding of the Precambrian geology of Ontario and the settings of mineral deposits (Fyon et al., this volume). PGS staff co-ordinate the geophysical surveys (Reford et al., this volume), bedrock geology compilation (Santaguida, this volume), and lithogeochemistry (Fyon et al., this volume) for this program.

Highlights of this program are described by Fyon et al. (this volume).

Ontario Mineral Exploration Technology Program

The Ontario Mineral Exploration Technology (OMET) Program was announced on September 15, 2000. The goal of OMET is to lever the Government's investment in innovative, collaborative, multidisciplinary technology and methods research projects to provide solutions to technical problems facing the mineral exploration industry in Ontario.

The Ontario Government committed new funds of $8 million, over 4 years, beginning in 2000-2001.

OMET will be administered through a partnership between the Ontario Ministry of Northern Development and Mines (Ontario Geological Survey) and Laurentian University (Mineral Exploration Research Centre).

OMET will focus research on three themes:

- best techniques to find mineral resources in bedrock beneath conductive or thick overburden. These conditions are common throughout Northern Ontario
- best methods to "see" through the Paleozoic rocks to explore for mineral resources, including diamonds, in the underlying Precambrian rock of the Hudson Bay and James Bay lowlands
- effective ways to utilize Ontario's Quaternary geology to explore for mineral resources buried in the bedrock.

The types of research projects that will be considered include:

- projects that develop a concept
- projects that prove a concept
- projects that demonstrate a concept or principle.

Other project types may be considered. Collaborative projects with potential to attract matching funds are desirable, but not obligatory. Additional details about the OMET program are available by request at: OMET@nickel.laurentian.ca.

INTER-JURISDICTIONAL AND COMMITTEE REPRESENTATION

PGS staff represent the Ontario Geological Survey on several inter-jurisdictional committees and associations, including:

1. Chair of the Committee of Provincial Geologists
2. Co-chair of the National Geological Surveys Committee
3. Mineral Exploration Research Centre, Laurentian University Board of Directors
4. Lithoprobe Western Superior Transect liaison
5. Secretary of the Canadian Exploration Geophysical Society (KEGS)
6. Chair, Geological Association of Canada, GIS Division
7. Executive of Sudbury Geological Discussion Group
8. Commissioner, North American Commission on Stratigraphic Nomenclature (until November 2002)
9. Precambrian-at-Large Representative, Joint Technical Program Committee, Geological Society of America
10. Adjunct professor at Carleton University, University of Ottawa, or Laurentian University.

ONTARIO GEOLOGICAL SURVEY ADVISORY BOARD

PGS provides executive support to the OGS Advisory Board and its geoscience Technical Committee. During the past year, the OGS Advisory Board and its Technical Committee met several times:

1. February 2000: Advisory Board met with Minister to discuss issues of priority to the Minister, Operation Treasure Hunt update, Mines Ontario update, and update on the implementation of OGS Technical Committee recommendations to OGS;
2. April 2000: OGS Technical Committee met with OGS to review OGS mapping program and Operation Treasure Hunt;
3. May 2000: OGS Advisory Board met to discuss an approach to First Nation issues at the request of the Minister;
4. June 2000: OGS Advisory Board and Minister's Mining Act Advisory Committee met to discuss submission of assessment information in digital format.

ADDITIONS TO THE SECTION

Jonathan Rudd joined the section in August 2000 as the staff geophysicist. Jonathan brings 10 years of industry experience. He will apply his geophysical skills and insight to support the bedrock-mapping program.

REFERENCES

Churchill, L.L. and Fyon, J.A. 1999. Project management - the information asset; *in* Summary of Field Work and Other Activities, Ontario Geological Survey, Open File Report 6000, p.45-1 to 45-5.

Table 1.1. Strategic thrusts of the Precambrian Geoscience Section: 1999–2000 and beyond.

STRATEGIC THRUST	OBJECTIVES	KEY INITIATIVES
Core Bedrock Mapping and Geophysics Program		
Understand the geology and metallogeny of high mineral potential areas (e.g., greenstone belts) in Superior Province.	a) Improve understanding of geology and mineral potential of key geographic areas that have not been mapped recently or that are inferred to contain important geological relationships, through systematic mapping and compilation at scales of 1:20 000, 1:50 000 and 1:100 000;	Western Superior NATMAP, Lithoprobe, (Thurston, this volume).
	b) Improve understanding of distribution of old and young crust that influence metallogenic patterns in western Superior Province;	Western Superior NATMAP (Thurston, this volume).
	c) Compile and interpret government and private sector regional airborne geophysics to enhance understanding of bedrock geology and mineral potential of the: a) exposed Sachigo Subprovince; b) Proterozoic substrate to Hudson Bay Lowland; and Archean substrate to James Bay Lowland.	Partnership projects with Geological Survey of Canada.
Understand provincial-scale relationships and settings of potential diamond-bearing rocks, rare-metal and/or petalite-bearing pegmatites, and platinum-group mineralization.	a) Improve understanding of, and mineral potential for, diamonds; b) Improve understanding of, and mineral potential for, sediment-hosted base-metal mineralization; c) Improve understanding of, and mineral potential for, rare-metal and industrial mineral (e.g., petalite) pegmatite mineralization; d) Improve understanding of, and mineral potential for, magmatic Ni-Cu-PGE mineralization associated with mafic intrusions and komatiitic flows.	Base program and collaborative projects.
Inventory key provincial-scale data sets relevant to mineral exploration.	a) Document distribution of FI-FIII rhyolite across the Superior Province; b) Revise metamorphic map of Ontario to better understand the spatial, temporal, and thermal relationships of mineral assemblages to the local tectonic history and metallogeny; c) Update and maintain geochronology database for Ontario.	Base program and collaborative projects.
Understand the geology and metallogeny of high mineral potential areas in the Grenville and Southern provinces.	a) Improve understanding of geological history and metallogeny of Grenville Province, Grenville Front, and Southern Province; b) Improve understanding of geology and controls on mineralization of Ni-Cu-PGE mineralization in the Sudbury Impact Structure, Nipissing intrusions, and Early Proterozoic, mafic intrusions.	Core program and collaborative projects.
Implement program support practices and instruments to address and refine the human resource strategy, digital data standards and program management practices.	a) Complete the design and documentation of the digital mapping tools, standards, and documentation; b) Complete the implementation of project management, human resource plans, and impact tracking practices, processes, tools, and databases.	Core program and specific projects.
Provide liaison role, representation, or support on behalf of the Mines and Minerals Division, the OGS, and PGS on committees, boards, meetings, or program needs.	a) Provide executive assistant support for OGS Advisory Board and its Technical Committee b) Provide support for planning sessions involving regional client associations c) Chair Committee of Provincial Geologists d) Co-Chair National Geological Surveys Committee e) Sit on Board of Directors of Mineral Exploration Research Centre f) Editor of the Canadian Exploration Geophysical Society (KEGS) g) Commissioner, North American Commission on Stratigraphic Nomenclature h) Precambrian-at-Large Representative, Joint Technical Program Committee, Geological Society of America	

Table 1.1. continued.

STRATEGIC THRUST	OBJECTIVES	STATUS
Add-on Geoscience Projects – Operation Treasure Hunt		
Contract and project management of airborne geophysical projects.	a) Overall project management; b) Procure proprietary airborne geophysical data; c) Provide and supervise QA/QC inspection services of airborne geophysical data.	a) Contract awarded to Paterson, Grant & Watson Ltd.; b) Stephen Reford is OTH Geophysicist.
Procure existing airborne geophysical data.	a) Acquire existing proprietary data; b) Disseminate acquired data to clients in client-desired formats.	Purchased about 113 000 line kilometres of proprietary airborne geophysical data.
Fly new airborne geophysical surveys over areas having mineral potential.	Time domain, frequency domain, and magnetic data to be acquired.	Seven survey areas completed, 105 000 line kilometres; project managed by Paterson, Grant & Watson Ltd.
Determine physical rock properties on surface rock samples collected from the Kirkland Lake and Matheson airborne geophysical survey areas, Abitibi greenstone belt.	Partnership with McMaster University.	Project underway.
Lithogeochemical surveys.	Identify areas having base metal potential.	Purchased lithogeochemical data describing volcanic rocks, originally collected by University of Saskatchewan project sponsored by CAMIRO.
Precambrian bedrock compilation.	a) Conducted over central Superior Province from Sudbury to Lake Nipigon area; b) Complements on-going Grenville, Abitibi, and western Superior Province mapping and compilation efforts.	Project underway.
Add-on Geoscience Project – Ontario Mineral Exploration Technology Program		
Administrative partnership with Mineral Exploration Research Centre, Laurentian University.	a) Techniques to find mineral resources in bedrock beneath conductive or thick overburden. These conditions are common throughout Northern Ontario. b) Methods to "see" through the Paleozoic rocks to explore for mineral resources, including diamonds, in the underlying Precambrian rock of the Hudson Bay and James Bay lowlands; c) Effective ways to utilize Ontario's Quaternary geology to explore for mineral resources buried in the bedrock.	Under development.

Table 1.2. List of Precambrian Geoscience Section collaborative projects.

Project Name	**Collaborators**
Sudbury ore deposit study	Geological Survey of Canada, Laurentian University, INCO Ltd., Falconbridge Ltd., University of New Brunswick
Holloway Township structural geology	University of Ottawa, Battle Mountain Gold, Barrick Gold Corp.
Lithogeochemistry of gold-associated alteration, Garrison to Marriot townships	University of Ottawa
Geochemistry and metallogenesis of komatiites in Ontario: compilation project	Mineral Exploration Research Centre, Laurentian University
Physical volcanology of komatiites in Ontario	Mineral Exploration Research Centre, Laurentian University
Geology and metallogenesis of sanukitoid	Mineral Exploration Research Centre, Laurentian University
Geology, stratigraphy, chemostratigraphy, and ore mineralogy of the River Valley intrusion	Mineral Exploration Research Centre, Laurentian University
Geology, stratigraphy, chemostratigraphy, ore mineralogy and metallogeny of Entwine Lake intrusion, Wabigoon Subprovince	Mineral Exploration Research Centre, Laurentian University
Time scales of formation of rare-metal pegmatites in Archean rocks	Open University
Structural controls on shear-hosted gold occurrences in the Beardmore–Geraldton Belt at the Quetico-Wabigoon Subprovince boundary	Laurentian University
Geology, volcanology, lithogeochemistry and alteration associated with volcanogenic base metal mineralization in the Big Four Lake area, Abitibi greenstone belt, Shining Tree	University of Ottawa
Kenogamissi batholith structural emplacement study	University of Ottawa
Lithoprobe – refraction seismic northwest Superior transect	Lithoprobe
Lithoprobe – reflection seismic northwest Superior transect	Lithoprobe
Evaluation of geophysical interpretation approaches for interpretation approaches for geological mapping and mineral exploration in greenstone belts	Geological Survey of Canada – Continental Geoscience Division, McMaster University, Institut de Physique du Globe, Paris
Volcanology and VMS-related alteration and mineralization of Marshall Lake, Archean felsic volcanic centre – eastern Wabigoon Subprovince	Laurentian University
Geochemistry and tectonic evolution of the Shining Tree area, southern Abitibi greenstone belt	Portsmouth University
Physical rock properties of samples from the Abitibi greenstone belt	McMaster University
Western Superior NATMAP	Geological Survey of Canada, Manitoba Geological Services Branch
GIS analysis of Red Lake greenstone belt	Geological Survey of Canada
Metamorphic map of Ontario	Geological Survey of Canada
Canadian Geoscience Knowledge Network	Geological Survey of Canada
Mineral potential assessment through modeling geophysical data	Geological Survey of Canada - Spatial Data Analysis Laboratory
Reprocessing of ODM/GSC geophysics	Geological Survey of Canada

2. Precambrian Initiatives and Regional Controls on Mineralization

P.C. Thurston

Manager, Bedrock Mapping and Geophysics, Precambrian Geoscience Section, Ontario Geological Survey

BACKGROUND

Fyon (this volume) has summarized the overall Precambrian Geoscience Section program at the level of partnerships with external groups and the major initiatives. The initiatives of the Precambrian Geoscience Section represent geographic or functional groupings and two styles of project execution:

1. Team initiatives in which individual projects are part of a tightly integrated whole, for example, the Abitibi initiative.
2. Project groupings in which several independent projects contribute to a larger scale goal. This situation represents the NATMAP initiative in which individual OGS and GSC projects contribute to the overall NATMAP goal described below. Toward the later stages of the NATMAP effort, integrated teams will produce regional scale compilations of the entire NATMAP area.

The Precambrian Geoscience Section program in fiscal 1999/2000 includes: three fully staffed projects and two projects with minimal staff and eleven partnership projects. The decrease in field projects from last year is the result of the initiation of the Provincially Significant Mineral Potential initiative. The individual partnership projects are listed in the preceding article (Fyon this volume). Those partnerships with a significant field component, or significant new results, are reported on in individual articles.

The major initiatives of the Section are: 1) NATMAP and LITHOPROBE (concentrated in northwestern Ontario); 2) the Abitibi initiative; 3) provincial projects including mapping in other areas and regional scale mineral deposit studies; and 4) program support. In recent years, we have attempted to split our efforts roughly as follows: Abitibi (35%), NATMAP and LITHOPROBE (30%), Provincial projects (30%) and program support (10%). However, while the above represents the normal allocation of Precambrian Geoscience Section resources, the arrival of the Provincially Significant Mineral Potential initiative required a fundamentally changed perspective. The Precambrian Geoscience Section has assigned five permanent staff to this initiative. The role to be played by the Precambrian Geoscience Section is described in the section below.

PROVINCIALLY SIGNIFICANT MINERAL POTENTIAL

The Ministry of Natural Resources Ontario's Living Legacy land use strategy will permit "controlled exploration" on those parts of new parks and conservation reserves in which there is "provincially significant mineral potential". The Resident Geologists Program has convened a multi-stakeholder committee to define what constitutes "Provincially Significant Mineral Potential" and will then produce a large-scale mineral resource assessment data set. This data set will consist of a geological layer overlain by polygons defined on the basis of mineral potential. The role of the Precambrian Geoscience Section in this initiative is to produce a 1:250 000 scale overview of the geology of the province. This effort will be accomplished as outlined in the article by Berger and Debicki (this volume). It must be emphasized here that this overview will be produced by updating, as much as possible in the time permitted, digital manuscript versions of the Geology of Ontario Bedrock map (OGS 1991). The resulting maps at 1:250 000 scale will differ substantially from compilation maps previously produced in that: 1) original geological sources will not be consulted; and 2) the digital manuscript maps will be updated based upon post-1990 mapping based solely upon the perceived economic importance of work done subsequent to 1990. Mineral deposit and mineral potential themes produced by staff of the Resident Geologist's program will be superimposed on the geological theme.

GEOLOGIC OVERVIEW

This section describes recent changes to the large-scale subdivisions of the Superior Province and their implications for exploration. Details are contained in the individual articles, but implications going beyond the boundaries of individual map areas are described below. Readers will note a lack of consistency in nomenclature relative to last year's discussion (Thurston 1999), a direct reflection of the rapidity of change in the area of tectonic subdivisions of the Superior Province. Nomenclature and tectonic subdivisions should stabilize as the NATMAP initiative moves to completion.

In the far north, the Uchi–Sachigo superterrane (Stott 1997) is composed of the North Caribou Terrane (a region of 2.9-3 Ga and younger Archean greenstones) bordered on the north by greenstones and granitoid rocks of 2.8-2.7 Ga age. The Stull–Wunnummin structure (Thurston et al. 1998) likely forms the north boundary of the North Caribou Terrane. Spatially associated with the structure are Timiskaming-style assemblages at Stull Lake and in the Blackbear Lake area (Stone and Hallé this volume). Given the presence of Timiskaming-style metasedimentary rocks and gold mineralization (Osmani and Stott 1988), the Stull–Wunnummin structure is likely a major structure and thus of importance in gold metallogeny (Stott and Berdusco this volume).

Skulski et al. (1999) have identified the presence of three broad age subdivisions in the far north: 1) the North Caribou Terrane; 2) an area north of the North Caribou Terrane likely of 2.7 Ga age and 3) north of the North Kenyon fault are likely correlatives of 3.4 Ga rocks of the Assean Lake area of Manitoba (Heaman et al. 1999). If this subdivision is valid as suggested by Stott and Berdusco (this volume) then they have identified a large area of circa 2.7 Ga greenstones worthy of attention for both platinum group elements and volcanogenic massive sulphide exploration given their age. Further insight into the scale and character of the North Caribou Terrane is seen in the work of Hynes (1999). He postulates that variations in the regional gravity field suggest the presence of large-scale folds. This view of the gravity field and the facing of greenstone fragments in the North Caribou Terrane is used to postulate a series of alternating anticlinoria and synclinoria involving the granitoid basement and greenstone belts of the North Caribou Terrane. Stott and Berdusco (this volume) clearly illustrate the extent of these terranes beneath the Hudson Bay lowlands. On the southern margin of the North Caribou terrane, the 2.7 Ga Confederation assemblage sits unconformably upon the 2.9–2.8 Ga rocks of the North Caribou Terrane (Sanborn-Barrie et al. 2000). Particularly important is the insight into the nature of the English River and Quetico subprovinces as interarc basins rather than the former notion of them as accretionary prisms (cf. Percival and Williams 1989).

As noted previously, the central Wabigoon region has been postulated to consist of two circa 3 Ga terranes (Stott et al. 1998). The presence of S type granites in the central Wabigoon may mark a major crustal structure (Stone and Hallé this volume). The platformal metasedimentary rocks in the northern extension of the Lumby Lake belt clearly mark this greenstone fragment as probably of circa 3 Ga age. The northeast-trending shear zone extending from the Atikokan area through Stone and Hallé's map area (this volume) likely marks the margin between the 2.7 Ga arc greenstones of the western Wabigoon and the platformal 3 Ga greenstones of the central Wabigoon region.

Ayer et al. (1999) described the main part of the Abitibi greenstone belt as an intact stratigraphic sequence developed above older granitoid. This is termed "ensialic" development or genesis in an environment in which the younger greenstones were erupted through the older units including older granitoid rocks. Similar patterns are seen in both the Swayze and Michipicoten greenstone belts to the west. This pattern in the Abitibi and Wawa subprovinces has brought about a model involving a smaller number of "super-assemblages" relative to the models of the 1990s. This has changed interpretation of the Abitibi from allochthonous exotic, that is, disconnected independent assemblages in the sense of Jackson et al (1994) to an autochthonous model similar to that developed by Heather et al (1996) for the Swayze greenstone belt to the west. This concept makes Abitibi subprovince assemblages more comparable in scale to the assemblages seen in northwestern Ontario.

These newly proposed subdivisions of both the Abitibi (Ayer et al. 1999) and the eastern and central Wabigoon subprovinces (Stott et al. 1998; Tomlinson et al. 1998) are key to more precisely assessing mineral potential, particularly lode gold mineralization and rare metal pegmatites. There are hints (Berger 1999) that we may have to pay more attention to the total structural picture to assess gold potential in that "cross faults" not directly related to major shear zones may also be the locus of lode gold deposits.

ABITIBI INITIATIVE

Several Abitibi initiative staff were assigned to projects in the Provincially Significant Mineral Potential project. The Abitibi initiative involves nine projects, one regular mapping project and eight partnership projects. The 1:100 000 Abitibi compilation has been supplanted by the need to complete the 1:250 000 compilation of the remaining Abitibi area under the Potentially Significant Mineral Potential project. The 1:100 000 compilation will next cover the area to the west of the Kirkland Lake map just released. Highlights of the Abitibi projects are listed below:

1. The 1:100 000 scale compilation involving J. Ayer, N. Trowell and L. Valade has issued the third sheet, as a digital and a hard copy map. This sheet is centered on the Kirkland Lake area. It is a so-called "smart" map in which data tables such as geochronology and mineral occurrence data are electronically linked to the map polygons. It is now apparent that the new "super-assemblage" concept is likely applicable to the Swayze greenstone belt and the Michipicoten greenstone belt.
2. Vaillancourt (this volume) reports on first year results from mapping to the west of Timmins. Mapping will continue in this area over several years.
3. Luinstra (this volume) is examining gold mineralization along the Porcupine–Destor deformation zone as a partnership project involving two industry companies, Ottawa University and the OGS. He describes evidence for two gold mineralizing events at the Holloway and Holt–McDermott mine.
4. Pigeon and others (this volume) describe results of an MSc level investigation of the petrology of the syenite suite associated with gold occurrences along the Porcupine Destor deformation zone.
5. Leblanc et al. (this volume) describe the early stages of investigation of the volcanology and mineralization in the Shining Tree greenstone belt. Mapping in the belt will be resumed upon completion of the Provincially Significant Mineral Potential Project.
6. Associated with the Shining Tree mapping is a PhD level examination of the geochemistry of the volcanic rocks. This study (Oliver and others this volume) summarizes geochemical evidence for ensialic development of the greenstones.
7. Becker and Benn (this volume) have commenced a study of the structure of the Kenogamissi batholith being approached by use of magnetic fabrics in the granite. This study will allow correlation of structural development within the batholith with structural development in the greenstone belt.

Such a study will shed light on the probable involvement of batholith derived fluids in genesis of Archean lode gold.

8. The Precambrian Geoscience Section has recently complemented its knowledge of Platinum Group element deposits through development of a partnership with the Mineral Exploration Research Centre at Laurentian University. Under this arrangement, R. Sproule and others are pursuing a study of the geochemistry of komatiite in the Abitibi subprovince. This study has provided powerful insight into the geochemical relationships between the four major "super-assemblages" constituting the bulk of the greenstones of the Abitibi greenstone belt. Sproule et al. (this volume) indicates that the four komatiite-bearing assemblages likely represent a 50 million years duration single plume event. This insight again strengthens arguments for ensialic development of Abitibi greenstones.
9. Again under the partnership arrangement with Mineral Exploration Research Centre, Houlé (Houlé et al. this volume) has commenced a PhD study of the facies of Abitibi komatiite. The study will provide direct insight into which particular part of Abitibi komatiite stratigraphy is most prospective for komatiite hosted nickel deposits.

NATMAP INITIATIVE

NATMAP is a Geological Survey of Canada program emphasizing regional mapping in collaboration with provincial surveys and academia. The Western Superior NATMAP project (Percival et al. this volume) will produce a series of 1:250 000 compilation maps of areas where either GSC or provincial surveys have done NATMAP field work. Within Ontario, that will include: 1) the Onaman–Tashota area, 2) the Sturgeon Lake–Savant Lake area, 3) the Confederation–Red Lake area and 4) the southern part of the central Wabigoon Subprovince. These areas will be knitted together by production, through the efforts of the GSC, the OGS and Manitoba Energy and Mines, of a 1:1 000 000 scale map of the Superior Province west of the Onaman–Tashota greenstone belt. Possible major tectonic subdivisions are illustrated in Figure 2.1 based upon recent work by Stott (1998), Tomlinson and others (1999) Stone et al. (1999) and Stone and Hallé (this volume). Similarly, there is some scanty evidence that the age of volcanism and shear zone development north of the North Caribou Terrane may young northward, reinforced by results obtained by Stone and Hallé (this volume) and Heaman and others (1999). Validation of these concepts will improve large-scale understanding and exploration effectiveness. The following paragraphs attempt to put into perspective the efforts of both the Precambrian Geoscience Section initiative and GSC projects in terms of recent results and future directions.

1. Stott and Berdusco (this volume) describe results of interpretation of the aeromagnetic data for the Precambrian beneath the Hudson Bay and James Bay lowlands. They erect a dramatically different view of the extent and character of the major tectonic subdivisions for this region. Particularly significant achievements are the identification of an inter-arc basin origin for the Quetico and English River subprovinces as well as metallogenically important observations on lode gold and rare metal pegmatites. The interpretation will play a future role in identification of major structures controlling emplacement of kimberlite magma.
2. Stone and Hallé (this volume) describe the last phase of field work on the far northern part of the Superior Province. This project, when compiled with recent advances in isotopic geochemistry in Ontario (Skulski et al. 1999) and in Manitoba (e.g., Heaman and others 1999) will profoundly modify understanding of this region.
3. Stone and Hallé (this volume) describe work in the southern part of the central Wabigoon region. An important achievement of this year's mapping was the possible delineation of the western margin of the central Wabigoon region in the form of a major shear zone extending about 170 km northeast from the Quetico fault near Atikokan.

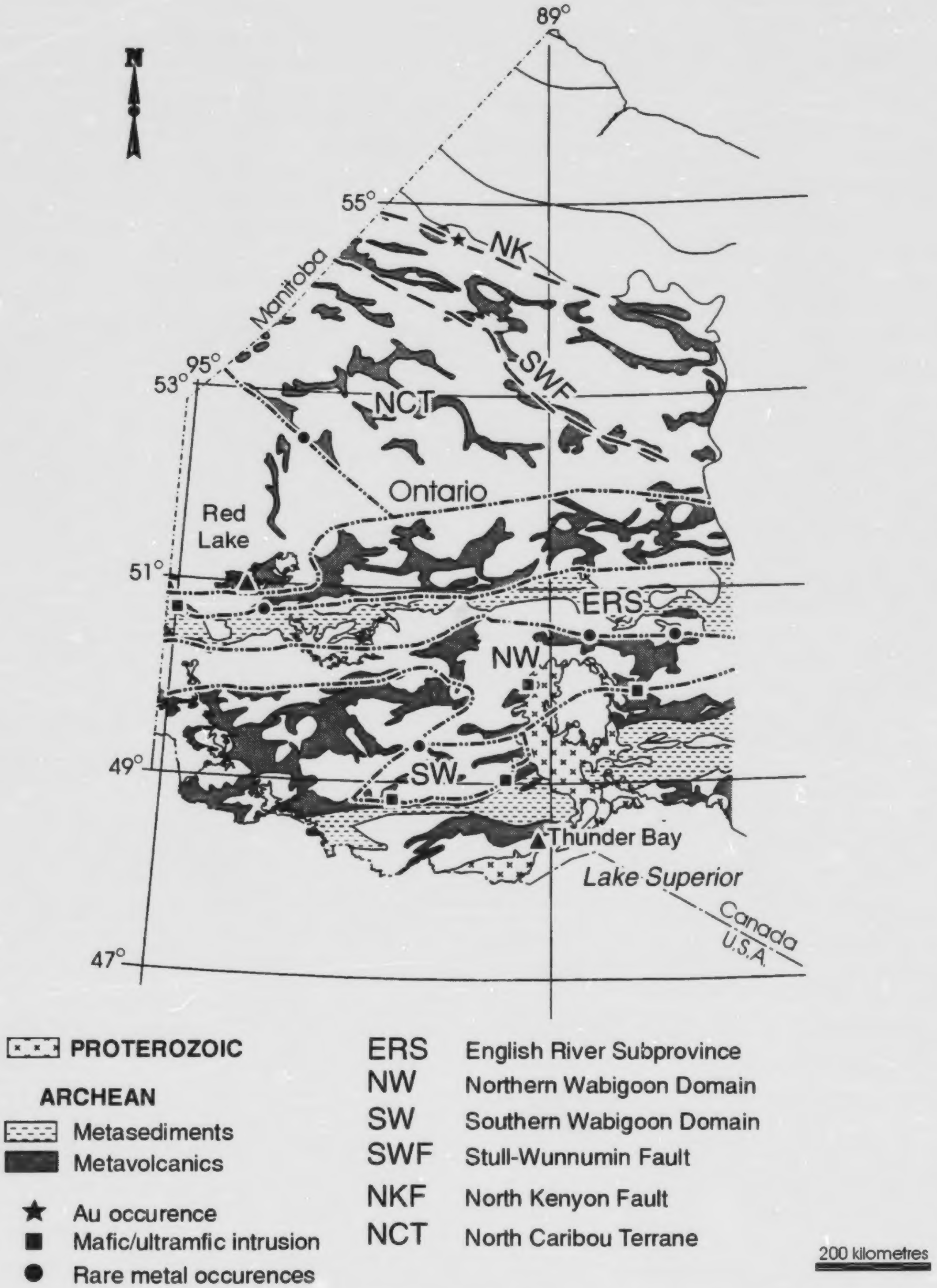

Figure 2.1 Generalized geology of the western Superior Province illustrating in a general way the newly proposed tectonic subdivisions and examples of the various mineral deposit types associated with tectonic boundaries.

4. Hart and Macdonald (this volume) mapped a region to the west of Lake Nipigon. Their articles clearly identify the interface between 2.9 and 2.7 Ga greenstones and provide insight into use of the Operation Treasure Hunt geophysical surveys in interpretation of both greenstones and granitoid rocks.
5. Beakhouse (this volume) has employed a magnetic susceptibility meter in investigation of plutonic rocks at Hemlo and in the course of his current mapping at Wabigoon (Beakhouse this volume). The meter allows insight into styles of granitoid related mineralization as well as field based solution of mapping problems in typical greenstone belt units. The meter has improved the ability to rapidly map within greenstones of the Wabigoon area.
6. Beakhouse (this volume) has commenced a multi-year study of the Wabigoon area. The mapping is intended to link the work to the south in the Manitou Stretch area (Smith 1990) with recent studies in the Sioux Lookout area (Devaney 2000; Berger 1989).
7. Arnold et al. (this volume) have commenced a study of PGE mineralization associated with the Entwine Lake pluton, a sanukitoid intrusion.
8. Parker (this volume), in close association with GSC mapping, has documented the character and extent of gold related alteration in the Red Lake greenstone belt. This work provides a context for mineralization at several properties other than the two currently producing mines. The spatial association of the alteration and deposits with the unconformity between 2.9 and 2.7 Ga stratigraphy has important regional implications.
9. Parker (this volume) identifies several intrusions at the west end of the Red Lake greenstone belt with potential for platinum group element mineralization.
10. Smith et al. (this volume) describe the first U–Pb dating of columbite-tantalite in Ontario. The results strongly link development of S type granites and generation of fractionated rare metal pegmatites at Pakeagama Lake and Separation Rapids. The work also highlights the continuing mystery about why we have magmatism as much as 50 million years after completion of cratonization at surface in two widely separated locales.
11. DeWolfe et al. (this volume) have commenced a structural study of the structural framework of gold mineralization in the Beardmore–Geraldton greenstone belt.
12. Straub et al. (this volume), in a continuation of a M.Sc level study of mineralization at Marshall Lake, provide a textural and geochemical description of alteration associated with volcanogenic massive sulphide mineralization.
13. Schwerdtner and Ahmad (this volume), in a partnership project, describe structural studies of granitoid rocks west of Thunder Bay.

OTHER INITIATIVES

Approximately 30% of the Precambrian Geoscience Section program is devoted to initiatives other than NATMAP and the Abitibi program. Projects under these initiatives include the following: 1) a comprehensive review of kimberlite magmatism throughout Ontario, 2) a study of regional controls on rare metal mineralization reported on under the NATMAP initiative, 3) continuing mapping and related work in the Grenville Province, and 4) commencement under Operation Treasure Hunt of 1:250 000 scale compilation centered on the Wawa subprovince.

Provincial Scale Projects

1. The kimberlite project led by Ron Sage, has two phases: a) kimberlite bodies in the Lake Timiskaming region and b) kimberlite bodies in the Attawapiskat region of the James Bay Lowlands.

A total of three Open File Reports have been prepared for release in the last 12 months. All should be released by the time this report is available.

2. Mike Easton has recently completed work on the Ontario portion of a metamorphic map of the Canadian Shield in production at the GSC. An external publication on significant aspects of the interpretation is complete.
3. Easton (this volume) as an outgrowth of the work on the metamorphic map, provides a far-reaching interpretation of controls on emplacement of 2.4 Ga platinum group element mineralization of the East Bull Lake Intrusive suite in the Sudbury region. Implied in the interpretation is the importance of mid-crustal level panels in localization of this mineralization. Similar panels present in the Kapuskasing structural zone and south of Wunnummin Lake may also represent similar tectonic environments.
4. Hrominchuk (this volume) provides further details on controls at the detailed scale for platinum group element mineralization in the Dana–Crerar Township area.

COMPILATION MAPS

The OGS bedrock compilation maps at about 1:250 000 scale were produced from the early 1960s through to the 1980s. No compilation projects at this scale have been done since the publication of the Geology of Ontario maps in the early 1990s. The exploration industry has clearly indicated the usefulness of this product in generation of new exploration targets. To meet this need, the Precambrian Geoscience Section has a four-pronged response:

1. In 1998 we produced the first of four 1:100 000 scale compilations that will result in complete coverage of the Abitibi subprovince.
2. Under the NATMAP program, the final product will be a joint OGS/GSC compilation at a scale of 1:1 000 000 of the Superior Province west of Lake Nipigon. The working scale manuscript maps at a scale of 1:250 000 will form the basis for re-issue of compilation maps for all of northwestern Ontario.
3. The remaining area will be compiled with funding from Operation Treasure Hunt over the next 18 months. 1:250 000 scale compilation maps of the Shebandowan (NTS 52 A,B), Wawa (NTS 42 C,D,E,F) and Sault St. Marie – Sudbury areas (NTS 41J, N, K) will be produced. Details are reported by Santaguida (this volume).
4. Compilation of the Grenville Province at 1:250 000 will be produced under the Potentially Significant Mineral Potential initiative and published subsequently.

SECTION SUPPORT

The Section has several projects designed to facilitate the mandate of the Section. These include a number of projects for standardizing and improving digital data flow (Berdusco 1999) and the geophysical program.

The Precambrian Geoscience Section has a new geophysicist, Jonathon Rudd. His role in the section will be mainly that of supporting the mapping effort through aiding interpretation of geophysical data.

IMPLICATIONS FOR REGIONAL CONTROLS ON MINERALIZATION

Several articles, in particular Stott and Berdusco (this volume) and Easton (this volume) have direct exploration implications at a provincial scale. An additional facet of greenstone belt geology is of critical importance. Greenstone belt mappers are accustomed to the presence in suitable locales of an unconformity between circa 2.6 Ga Timiskaming-style assemblages and older, underlying Keewatin-style assemblages. Recent mapping by Stone and Hallé (this volume) has identified a similar relationship in the Stull Lake area. Work by the GSC and the OGS (Sanborn-Barrie et al. in press; Parker this volume) describe the importance of the unconformity between 2.9 and 2.7 Ga stratigraphy in the Red Lake greenstone belt. The unconformity is marked by the presence of polymictic conglomerate and variable younging and structural facing relationships. Subtle unconformities are present in greenstones of the Pilbara and the Baltic Shield as well. This, coupled with the ensialic model for development of Abitibi greenstone belts, suggests that many greenstone sequences contain subtle unconformities within them. If this is the case, Archean stratigraphy may bear a strong resemblance to modern "sequence stratigraphy" in which unconformity bounded packages are central to stratigraphic interpretation (cf. Miall 1994). If we can implement such a model in greenstone belt stratigraphy, belt-to-belt correlation may be somewhat easier to accomplish, aiding in syngenetic mineral deposit exploration.

The process of erecting new subdivisions in the far north of the Superior Province and the Wabigoon subprovince is not complete. Clues to the location of additional sutures are provided by features such as mafic/ultramafic intrusions which can provide indications of cryptic sutures between major crustal blocks. Examples to consider carefully include Lac des Iles, the Awkward Lake gabbro and the Chrome Lake intrusion in the Obonga lake greenstone belt (Blackburn et al. 1991; Percival et al. this volume).

The establishment of the larger scale assemblages in the Ontario part of the Abitibi greenstone belt (Ayer et al. 1999) may well have implications for the existing models of age variations across the Abitibi (Jackson and Fyon 1991) and the extent of these units from east to west.

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3. The Abitibi Greenstone Belt: A Program Overview

J.A. Ayer

Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Abitibi greenstone belt is the world's largest Archean greenstone belt covering an area of approximately 100 000 km^2. The Ontario portion constitutes about 30% of the belt and is a highly productive part of the province with respect to metal production. The Precambrian Geoscience Section program is designed to facilitate exploration by providing current geological mapping covering the areas of high economic potential at a variety of scales. We are also actively involved in research on the metallogeny and tectonic evolution of the belt and applied research on specific mineral deposit-related problems through so-called "partnership" projects. The applied research "partnership" projects are jointly funded by the Precambrian Geoscience Section, mining companies, the geology departments of several universities and other government agencies.

NEW DEVELOPMENTS IN THE ABITIBI

Geological models for the Abitibi greenstone belt are changing rapidly. The Precambrian Geoscience Section has profoundly modified the understanding of Precambrian greenstone belts by the advancement of the assemblage concept (Thurston and Chivers 1990). Jackson and Fyon (1991) applied the concept to the Abitibi Subprovince in Ontario and identified 71 assemblages. Jackson et al. (1994) interpreted the Abitibi greenstone belt assemblages as Archean analogues to a variety of modern geodynamic settings representing largely allochthonous terranes juxtaposed into their current positions by plate tectonic processes along active continental margins. However, recent mapping and geochronological determinations have led to reinstatement of the more traditional autochthonous stratigraphic model for the southern Abitibi greenstone belt, revealing that when unfolded, a largely coherent stratigraphic succession with similar ages and rock types exists in the Abitibi greenstone belt (Heather et al. 1998, Ayer et al. 1999a). The autochthonous model is also strongly supported by widespread evidence of inherited zircons representing the ages of underlying stratigraphy within the overlying volcanic units, thus indicating that upper stratigraphic volcanic units erupted through older units.

Tectonostratigraphic revision utilizing new geochronologic data, and the results of regional scale compilation has resulted in subdivision into 9 distinct stratigraphic assemblages identified on the basis of geochronological, lithological and temporal criteria (Ayer et al. 1999a). Understanding of the distribution of stratigraphic units has economic as well as scientific importance, because the significant mineral deposits are restricted to specific stratigraphic entities or chronological events in the >70 million years of Abitibi greenstone belt supracrustal history.

CURRENT PROJECTS

To date, the Abitibi compilation project has produced hardcopy and digital versions of the Timmins, Lake Abitibi and Kirkland Lake map areas and will continue to produce maps covering the Abitibi greenstone belt in Ontario at a scale of 1:100 000 (Ayer and Trowell 1998, Ayer et al. 1999b, Ayer and Trowell 2000). The compilation maps, in conjunction with new geochronological and geochemical sampling, enable further review of the assemblages, establishment of a more formalized stratigraphy, and the erection of new metallogic and geodynamic models for the evolution of the Abitibi greenstone belt. An additional phase of the project to be undertaken in conjunction with the Ministère de l'Énergie et des Ressources du Québec, will provide an unified set of English and French compilation maps covering the complete Abitibi greenstone belt at 1:250 000 scale. Data collection for the compilation project is being supplemented by more detailed mapping and research projects at a variety of scales (discussed below) in both provinces. The Ontario-based projects are designed to focus on areas where we currently have an inadequate understanding of the relationships between mineralization and geology.

A new program began this summer in the Timmins West area with the 1:20 000-scale mapping of Bristol and Ogden townships (Vaillancourt, this volume). This is a multiple year project with mapping to continue towards the west and south, covering a corridor surrounding the western portion of the Porcupine–Destor deformation zone. The main purposes of this project are to revise and develop improved knowledge of the nature and relationships between the different rock units in light of the new geological and geochronological studies in the area (Ayer and Trowell 1998, Ayer et al. 1999a) and to describe the structural deformation and the geochemical variations in hope of providing guidance for the very active exploration in this area. A research project to study the relationship between the different episodes of deformation along the Porcupine–Destor deformation zone in Ogden township was also begun in conjunction with the mapping. Preliminary results are presented by Dinel and Benn (this volume) and a B.Sc. thesis is expected by May 2001.

Over the past decade, Ben Berger has mapped a continuous swath of townships centered along the Porcupine–Destor deformation zone from Timmins to the Quebec border. This is an economically important area where several gold mines have recently been opened and a number of gold and base metal prospects are in various stages of evaluation. This mapping has revealed a number of important lithological, structural and stratigraphic factors (Berger 2000) which appear to be critical in focussing gold mineralization along the Porcupine–Destor deformation zone. Under the auspices of B. Berger's mapping program, two thesis projects are being conducted on problems related to the controls of gold mineralization. They are: 1) a Ph.D. thesis funded by the Precambrian Geoscience Section, the University of Ottawa and two mining companies has the objective of evaluating the timing and structural controls on the gold ore at the Holloway Mine and Holt–McDermott mines (Luinstra, this volume); and 2) an M.Sc. thesis studying the petrogenesis of the syenitic plutons in proximity to the Porcupine–Destor deformation zone east of Matheson and their genetic relationships to gold mineralization (Pigeon et al., this volume).

The Shining Tree greenstone belt has received a significantly increased level of exploration for gold and base metals following the opening of the former Temagami land caution area in 1996. The increased exploration interest and the need to integrate this poorly understood area with the remainder of the Abitibi greenstone belt has led to an ongoing project (Johns and Amelin 1999) which will ultimately provide a new 1:50 000 scale map and report for the 12 townships covering the belt. An ongoing Ph.D. thesis project at University of Portsmouth, UK is documenting the geochemical patterns of the various Archean rock packages in the Shining Tree greenstone belt (Oliver et al. this volume). This data will be used in conjunction with the mapping of G. Johns to help evaluate the evolution and geodynamic framework of this part of the Abitibi greenstone belt. In addition to this, a new M.Sc. research project was initiated in Macmurchy Township this summer (Leblanc et al., this volume). The objective of the research project is to describe and characterise the base metal and gold mineralization in the area. Samples collected from mapping and drill core of both mineralized and unmineralized rocks will be studied in thin section and analysed for major and trace elements in order to better understand their petrogenesis, and to determine the style of hydrothermal alteration and mineralization.

An ongoing collaborative project with the Mineral Exploration Research Centre (MERC) at Laurentian University has the goal of examining the spatial and stratigraphic variations in Abitibi greenstone belt komatiite in order to provide constraints on their petrogenesis and the stratigraphic architecture and assembly of the Abitibi greenstone belt (Sproule et al., this volume). In addition, a Ph. D. research project was initiated this summer with the aim of studying the volcanic facies of komatiite in the Abitibi greenstone belt in order to constrain stratigraphic, tectonic and metallogenic models (Houlé et al., this volume). These projects will help us to understand if komatiite within individual assemblages possess distinctive geochemical and/or facies types and whether komatiite-associated Ni-Cu-(PGE) deposits in the Abitibi greenstone belt occur at specific stratigraphic levels and in association with specific lava facies or magma types? The ultimate goal of this research is to aid in the exploration for new magmatic Ni-Cu-(PGE) sulphide deposits.

Finally, a new post doctoral research project co-funded by Precambrian Geoscience Section, University of Ottawa and the German Research Foundation (DFG) has begin studying the role of the large granitoid intrusions in the Abitibi greenstone belt. The study concentrates on fabric development in a batholith to correlate deformational processes in batholiths with those in the greenstone belts. This work will ultimately help understand the role of batholiths in providing structures and fluids for greenstone belt mineralization. The chosen working area of the Kenogamissi batholith (Becker and Benn, this volume) is structurally comparable to other granitoid intrusions in Archean greenstones and can therefore provide information on crustal and mineral deposit development during the last stages of the formation of continental crust. Since these intrusions usually only contain minor, if any, mineral deposits they are not as well characterized, therefore little is known about the mechanisms of granitoid intrusions in Archean cratons. More rarely is the connection of the emplacement history of batholiths with the evolution of the bordering greenstones and mineralization the subject of a thorough study. This information can be used to develop a model for the evolution and crustal formation of the craton, including possible mineral deposits in the host rocks of the batholith.

CONCLUSIONS

In summary, many exciting new advances in our understanding of the geology of the Abitibi greenstone belt are being made. The following reports in this volume demonstrate the merits of a diverse but balanced approach to Abitibi geology using the traditional strengths of Precambrian Geoscience Section mapping, the comphrensive understanding of the ore deposits by the mining companies and the research skills of university geology departments. This balanced approach embraces projects at the wide variety of scales and methodologies that are required for the range of problems that exist. The projects range from belt-wide compilation, to regional synoptic mapping, to township and down to extremely detailed mine scale mapping. The program is also focussed on the economically important parts of the belt in Ontario. We feel our integrated approach to applied research through collaboration with many of our mining company clients and the earth science departments of a number of universities is needed to advance our understanding of the geology and its relationship to mineral deposits in this geologically complex, but highly prospective, part of the province. We also feel confident that the maps, reports and theses resulting from this comprehensive program will provide many new ideas and concepts that are, and that will continue to be, directly applicable to exploration for new mineral deposits.

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4. Project Unit 00-011. New Geological Mapping and Compilation in the Timmins West Area – Bristol and Ogden Townships

C. Vaillancourt

Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Because of substantial recent geological and exploration work, and, therefore, the generation of new data, the remapping and compilation of the Timmins West area was undertaken at 1:20 000-scale. This past summer's mapping of Bristol and Ogden townships was the beginning of a multiple year project expected to continue toward the west and possibly the south, covering a corridor surrounding the western portion of the Porcupine–Destor deformation zone. The main purposes are to revise and develop improved knowledge of the nature and relationships between the different rock units in light of the new geological and geochronological studies in proximity of the map area (Ayer et al. 1999a, 1999b) and to describe the structural deformation and the geochemical variations in hope of providing a guide for the currently very active exploration by companies and prospectors.

The map area is located directly southwest of the city of Timmins and represents approximately 200 km^2. It is easily accessible directly from Highway 101 by logging roads, mainly Malette Road for Bristol Township and the extension of Pine South Street for Ogden Township, and other gravel roads and trails. Some remote parts of the area can also be accessed by boat on the Mattagami and Tatachikapika rivers.

Previous geological work as well as past exploration projects and mining activity in the area are summarised by Pyke (1982a) and Carlson (1967a). Detailed mapping was completed at 1:12 000 by Ferguson (1957) and at 1:15 840 by Carlson (1967b) in Bristol and Ogden townships, respectively. Pyke (1982b) produced a 1:50 000-scale compilation with added new data covering the township of Ogden and the easternmost part of Bristol. Recent 1:100 000-scale compilation of the Timmins area by Ayer and Trowell (1998) also covers Bristol and Ogden townships.

Access to diamond drill core and logs along with geological and geophysical data was kindly provided by Cameco Gold Inc., East West Resources Corp., Echo Bay Mines Ltd., Explorers Alliance Inc. and Placer Dome Inc. for examination and addition of important information to the map. Additional geological and geophysical data in the assessment files from the Resident Geologist's Office, Ministry of Northern Development and Mines, in Timmins was also compiled.

Given the poor exposure conditions of several sectors of the map, the integration of the exploration and geophysical data with the outcrop mapping is critical for the general interpretation of the area.

REGIONAL SETTING

Archean metavolcanic rocks of various compositions and affinities and metasedimentary rocks, largely turbidites, cover most of the map area and are intruded by rare small felsic plutons. Proterozoic diabase dikes of three different swarms cut the Archean rocks.

Located along the easternmost section of the Porcupine–Destor deformation zone, the map area includes rocks of various assemblages as defined by Ayer et al. (1999a). They are the Deloro, Kidd–Munro, Tisdale and Porcupine assemblages and are summarized below. Figure 4.1 is a sketch-map of the area representing the various lithologies and some structural components. Only the major diabase dikes are indicated for clarity.

The Deloro Assemblage

The redefinition of the Deloro assemblage by Ayer et al. (1999a) includes both the Deloro and Eldorado assemblages of Jackson and Fyon (1991). The assemblage is composed of calc-alkaline mafic to felsic metavolcanic rocks and intercalated banded iron formations located at or near the stratigraphic top. Multiple U-Pb dating of zircons all give ages near 2725 Ma (Corfu 1993, Ayer et al. 1997, Barrie and Corfu 1999) for this assemblage.

The Kidd–Munro Assemblage

The Kidd–Munro assemblage can be subdivided into a tholeiitic to komatiitic suite and a calc-alkaline suite with an age range of about 2717 to 2712 Ma (Ayer et al. 1999a). Only rocks of the former were observed in the map area and represent the units that Jackson and Fyon (1991) had classified in the Carscallen assemblage.

The Tisdale Assemblage

Three distinct lithological suites constitute the Tisdale assemblage. They are tholeiitic to komatiitic rocks with local rhyolite, intermediate to felsic calc-alkaline pyroclastic rocks and iron formations. They range in age from about 2708 to 2702 Ma (Ayer et al. 1999b). From this assemblage redefined by Ayer et al. (1999a), tholeiite and komatiite of the Tisdale assemblage of Jackson and Fyon (1991) and rhyolite of their Kamiskotia assemblage are present in the map area. A conformable contact between ultramafic flows of the Tisdale and felsic tuffs of the Deloro was observed in Ogden Township. This indicates a disconformity because of the absence of the Kidd-Munro and Stoughton–Roquemaure assemblages, which are found between them in other portions of the Abitibi greenstone belt (Ayer et al. 1999b).

The Porcupine Assemblage

The Porcupine assemblage defined by Ayer et al. (1999a) is composed of metasedimentary rocks, mostly wacke, siltstone and mudstone with minor conglomerate and is restricted in age to between 2698 and 2690 Ma. The portion present in the map area corresponds to the Hoyle assemblage of Jackson and Fyon (1991).

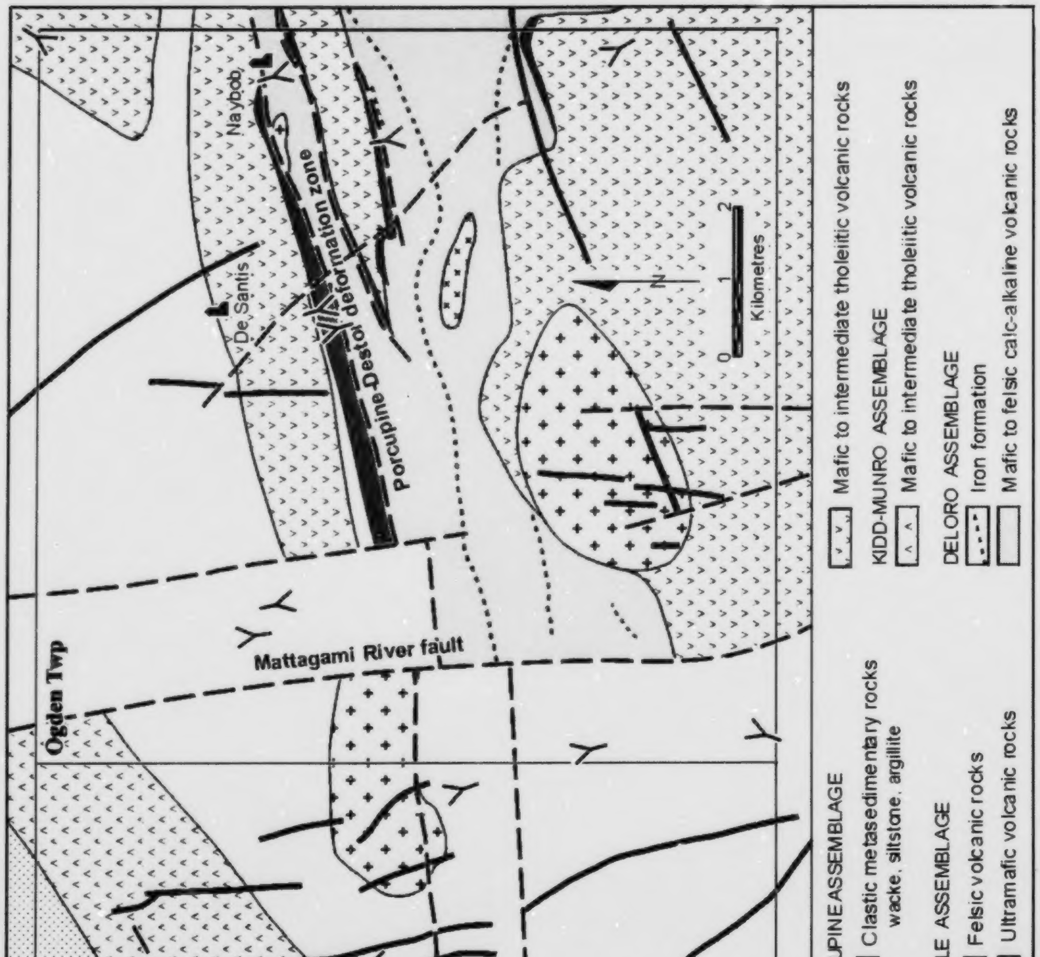
Ogden Twp
Bristol Twp
Mattagami River fault
Porcupine-Destor deformation zone
Naybob
De Santis
Holmer
Bristol fault
Allerston shear zone
N
0
1
2
Kilometres
Younging direction
Faults
Diabase dikes
Felsic intrusive rocks
qz-fp-porphyry, granodiorite
Mafic and ultramafic intrusive rocks
dunite, pyroxenite, gabbro, lamprophyre
PORCUPINE ASSEMBLAGE
Clastic metasedimentary rocks
wacke, siltstone, argillite
TISDALE ASSEMBLAGE
Felsic volcanic rocks
Ultramafic volcanic rocks
Mafic to intermediate tholeiitic volcanic rocks
KIDD-MUNRO ASSEMBLAGE
Mafic to intermediate tholeiitic volcanic rocks
DELORO ASSEMBLAGE
Iron formation
Mafic to felsic calc-alkaline volcanic rocks

Figure 4.1. General geology of Bristol and Ogden townships.

DESCRIPTION OF ROCK UNITS

Felsic Metavolcanic Rocks

There are two different packages of rocks that include felsic metavolcanic rocks in the map area. The first one is composed of massive rhyolitic flows and associated hyaloclastite and breccia. They cover the northwestern corner of Bristol Township and are interpreted to be part of the Tisdale assemblage. Tuffs and lapilli-tuffs forming the top of the Deloro assemblage in Ogden Township constitute the second felsic metavolcanic package of the map area.

MASSIVE RHYOLITE AND BRECCIA

The massive rhyolite and breccia are usually white on weathered surface but their fresh surface varies from dark grey to almost black when unaltered, to pink-orange, as a result of hematisation, or greeny beige, possibly from chlorite and/or epidote alteration. All massive rhyolite observed contains rounded to locally euhedral quartz phenocrysts averaging 0.5 mm in size. This texture is a very useful characteristic, especially in instances where the rocks are heavily altered and sheared as the quartz eyes are preserved. Well preserved flow banding was locally observed in the massive flows.

The rhyolite appear to become more fragmental toward the south and east. Lapilli-tuffs and heterolithic breccia are abundant in the centre of Bristol Township. The fragments are locally variable in texture and grain size but they are compositionally similar and contain the same quartz eyes as the massive flows. These breccias are host to gold prospects currently under investigation by Explorers Alliance Corp.

No plagioclase phenocrysts were observed macroscopically but further petrographic studies and geochemical analysis will be required to more fully characterize the rhyolite and identify trends in the textural or compositional variations.

TUFF

The size of the fragments in the tuff varies from fine ash to 2–3 cm lapilli and quartz and feldspar crystals represent an appreciable fraction. They are white on the weathered surface and pale grey on the freshly cut surface. Most of the outcrops of these units are located in the vicinity of the Porcupine–Destor deformation zone and are therefore strongly sheared although well preserved areas still reveal primary bedding and grading.

It appears that the felsic units of the Deloro are more abundant toward the top of the assemblage. However, they were also observed further south, within the more mafic units of the Deloro. It is possible that felsic units are stratigraphically intercalated with the intermediate units but it is more probable that suspected large-scale folds with east-northeast axial planes are responsible for the repetition. Cross laminae in a fine tuffaceous unit located close to the contact give facings which confirm the chronology between the Deloro tuff and the overlying Tisdale ultramafic flows.

Mafic to Intermediate Metavolcanic Rocks

Mafic to intermediate tholeiitic pillowed flows and tuff cover the centre part of Bristol Township. They are interpreted to be part of the Kidd–Munro assemblage on the basis of an age obtained on a sample from this same package of rocks a few kilometres to the west, in Carscallen Township (Ayer et al. 1999b). Other tholeiitic mafic metavolcanic units in the map area comprise high iron tholeiite (possibly icelandite) observed within the rhyolite at the northwestern corner of Bristol Township and flows of the Tisdale assemblage in Ogden Township.

The calc-alkaline volcanic rocks of the Deloro assemblage in Ogden Township contain abundant felspar and also local quartz phenocrysts reflecting a more intermediate composition.

THOLEIITIC ROCKS

The tholeiitic mafic metavolcanic rocks vary in color from light green to almost black, partly reflecting changes in composition from andesite to basalt and also the degree of carbonate alteration. Pillowed flows with pillow breccias are the most abundant lithologies but lapilli tuffs and breccias were observed in the centre of Bristol Township, close to the contact with the felsic flows. The exact nature of these breccias is not very well understood because they are very strongly sheared and further petrographic work will be required.

The pillows rarely have a typical rounded morphology, as they are most commonly amoeboid in shape. Facings are therefore difficult to interpret from the cusps since they are not distinct from other irregularities around the pillows. However, sequences of massive and pillowed flows with pillow breccias forming single flows of less than 5 m in thickness were used for younging directions.

CALC-ALKALINE ROCKS

Tuff and crystal tuff are the most commonly observed lithologies but massive and pillowed flows are also present. The level of alteration and deformation that most of these rocks have undergone has erased many of the primary textures leaving a massive appearance. The common presence of the feldspar phenocrysts and the less mafic composition are the main characteristics distinguishing them from the mafic tholeiites of the Tisdale assemblage. No direct contact between the two was observed and petrology and geochemistry along with the use of geophysical maps should help in defining a more precise location and trend for that contact.

Ultramafic Metavolcanic Rocks

In central Ogden Township, komatiitic flows of the Tisdale assemblage close to or at the contact with the felsic tuffs of the Deloro assemblage to the south are much more abundant than indicated on the previous geological maps. The reason is that extensive stripping and trenching only recently exposed them.

The ultramafic flows have undergone very intense shearing and alteration and are commonly transformed into schist containing abundant carbonate minerals, talc and apple green micas (possibly fuchsite). Where less deformed, spinifex and cumulate textures typical of ultramafic flows were observed but primary textures are seldom preserved. Successions of oriented spinifex, random spinifex and cumulate zones in specific flows were locally used to indicate top directions.

Iron Formation

Banded iron formation is interbedded with tuffs and lapilli-tuffs of the Deloro assemblage. They appear to be more abundant toward the top of the assemblage, near the contact with the ultramafic rocks of the Tisdale assemblage. They range in thickness from a few centimetres to about 3 m and appear to be discontinuous, as they can't be followed for a very long distance laterally. Because of the highly fragile nature of the banded iron formation compared to the calc-alkaline tuff that host them, the smaller interbeds located in highly sheared areas are dissected into small centimetre-scale rounded blocks that could be confused with xenoliths. However, local remobilization of the tuff may have produced a very similar rock but the apparent lateral alignment of the blocks supports the former interpretation.

The iron formations are composed of magnetite-rich bands intercalated with siliceous grey bands or jasper. The distinct black and pale grey or pink beds are 2 mm to about 1 cm in average but smaller scale laminations within the beds themselves is also visible. They have locally undergone intense intraformational brecciation where white to transparent quartz is the matrix to shifted blocks of the iron formation in which the original bedding and other primary textures are only poorly preserved.

Clastic Metasedimentary Rocks

Metasedimentary rocks of the Porcupine assemblage cover an appreciable portion of the map area but very few outcrops are present. Turbidite sequences of wacke, siltstone and argillite are the major components. Minor polymictic conglomerate interlayered with sandstone were also observed locally. The contact between the sediments and the underlying volcanic rocks of the Kidd–Munro assemblage in Bristol Township is folded and both units are sheared. Deformation in the volcanic rocks has destroyed all primary features and it is thus not possible to clearly identify if the contact is conformable or not. No direct contact between the sedimentary rocks and volcanic rocks were observed on outcrops in Ogden Township and alteration and deformation obscure those studied in core.

ARGILLITE AND WACKE

Clastic metasedimentary rocks of the Porcupine assemblage are usually immature and poorly sorted. Thick wacke units are composed mostly of quartz and plagioclase with a clay-rich matrix. Beds containing coarser lithic fragments were also observed locally. Interlayered pale gray siltstone and black, commonly graphitic argillites are well laminated. Abundant quartz and carbonate veins with local pyrite always cut them.

Grading in the sedimentary rocks is very common and was used for the determination of possible younging direction. Flame structures, where present, were a more reliable indication of tops. The metasedimentary rocks are locally transformed into sericite or biotite-schist by the major deformation zones. Folding was commonly observed on outcrops and in diamond-drill core.

CONGLOMERATE

Polymictic conglomerate of uncertain affiliation was observed in diamond-drill core at the contact between the ultramafic flows to the north and the felsic and intermediate calc-alkaline tuffs to the south. The very stretched pebbles are dominantly volcanic rocks of different textures and compositions, from felsic quartz porphyritic to ultramafic. The matrix is rich in quartz and contains small specks of pyrite and sericite. The pebbles and matrix are both variably silicified and carbonatized. Detailed description and understanding of this conglomerate will require petrographic work.

Ultramafic and Mafic Intrusive Rocks

METAGABBRO AND DIORITE

Small gabbroic and dioritic intrusions and dikes cut the volcanic rocks in the area. They are most commonly fresh looking and not much affected by deformation. They are composed of pyroxene and plagioclase and some contain smaller amounts of quartz and potassium-feldspar. Both ophitic and porphyritic textures were observed in different intrusions and dikes. The grain size varies largely from near aphanitic to coarse (around 2 mm-large pyroxenes). These units most likely represent synvolcanic intrusions and linking them to the volcanic rocks will be attempted with further study.

CARBONATE-RICH INTRUSIONS

A carbonate-rich intrusion was observed in southern Bristol Township. It is composed of multiple injections of different grain size and possibly composition. Large polygonal and needle-shaped pyroxenes were observed but the most common units have smaller crystals. All units are highly magnetic due to the omnipresence of magnetite in variable amounts. Books of dark mica (biotite or phlogopite) were also observed locally. Well-preserved areas are scarce and most samples collected are extremely sheared and altered. Different authors gave a variety of interpretations about the nature of this unit. Ferguson (1957) mapped it as a pyroxenite. Barrie (1990) referred to these rocks as part of a lamprophyre suite. The terms fenite and carbonatite were also found in the description of the intrusion in assessment files. Extensive petrographic work and geochemical analysis will be required to come to a better understanding of this intrusion and to further comment on previous interpretations.

Felsic Intrusive Rocks

PORPHYRIES

Various porphyritic intrusions are present in the map area. Two large bodies are located in the center and east of Bristol Township and are of interest for their gold potential. Smaller porphyritic intrusions and dikes are found in central and eastern Ogden Township. Variable amounts of pyrite, chalcopyrite and visible gold were found in the porphyries. The age relations and metamorphosed state of these units suggest they are subvolcanic equivalents of the volcanic units.

These units commonly have both quartz and feldspar phenocrysts although they can also contain only one of the two minerals. They are rounded and the size of the phenocrysts varies between less than 1 mm to about 4 mm. Biotite appears to be the most common mafic mineral in the porphyries but it is never a major component of the rock. The feldspar phenocrysts are partly to fully replaced by quartz and the groundmass is also commonly silicified. All porphyritic bodies studied contain abundant carbonate minerals. Potassic alteration locally gives an orangy-pink color to the porphyries. Sericitisation and local chlorite or epidote alteration were also observed in the porphyry.

Abundant quartz-carbonate, quartz-tourmaline and less frequently quartz-chlorite veins cut across the different porphyritic bodies.

SYENITE

A small syenitic body with a diameter of about 600 m is located in the southwest of Bristol Township. Various textures were observed within this intrusion, from near aphanitic to porphyritic with feldspar phenocrysts up to 6 mm in size. The different phases appear to be injected into one another. The colour of the weathered surface is rusty pink and that of the fresh surface varies from pinkish grey to orange. The larger phenocrysts display well-defined zoning. This rock is reactive to acid, revealing the presence of carbonate minerals. It is very locally slightly magnetic. The well preserved textures suggest this unit is relatively late.

Small felsic dikes were observed in the volcanic rocks west of the syenitic pluton and could be associated with it. Local areas in the dikes contain over 20% large magnetite crystals. Petrography and geochemistry will be required to associate or not the dikes with the syenite.

Diabase Dikes

Dikes of three different swarms occur in the area. They are the northwest-trending Matachewan swarm of Paleoproterozoic age and the Mesoproterozoic east-northeast-trending Abitibi swarm and west-northwest-trending Sudbury? swarm. Only a few of the dikes encountered are shown on Figure 4.1 but many more can be interpreted from the aeromagnetic data.

METAMORPHISM

The regional greenschist-facies metamorphism is clearly dominant in the area. Very few effects of contact metamorphism were observed because of the absence of large batholiths in or near the area, compared to other portions of the Abitibi greenstone belt. However, mafic volcanic rocks located in the southwestern corner of Bristol Township along Highway 144 appear to have suffered some effects of contact metamorphism. They are darker then the similar units to the north and the pillow selvages are starting to fade. It is possible that either the syenitic pluton or the carbonate-rich ultramafic intrusions located only a few kilometres east of this area extend at depth. The presence of a magnetic high underlying the volcanic rocks and approximately on strike with the ultramafic intrusion supports this interpretation.

STRUCTURAL GEOLOGY

The structural history of the area is highly complex with evidence for the superimposition of at least three distinct episodes of deformation. These have resulted in very complex structural patterns. The relative rarity of reliable younging indicators in the stratigraphy introduces another element of complexity in the structural analysis of the map area.

The first established event is mostly expressed by an intense east-northeast to east schistosity referred to as S_1. F_1 folds with sub-vertical axial planes were recognised locally at the outcrop scale and larger folds are suspected from facing reversals in stratigraphy. S_1 is parallel to the Porcupine-Destor deformation zone (PDDZ; Figure 4.1) which is interpreted to be continuous possibly from the Kapuskasing structural zone into Quebec (Jackson and Fyon 1991). The Allerston and the Bristol shear zones (Figure 4.1) are also areas of concentration of D_1 deformation. Intense carbonate alteration also appears to concentrate along the east-west deformation zones but it also affects lithologies across the entire map area to a lesser extent.

Well-developed crenulation is the most commonly observed effect of the subsequent deformation event (D_2). The sub-horizontal lineation formed at the intersection of D_2 crenulations with the S_2 schistosity plane was noticed all across the map area. Metre scale folds with axes shallowly dipping toward the east-northeast to west-southwest also represent a local manifestation of this episode of deformation.

Folds resulting from D_3 with steeply dipping axes and northeasterly oriented axial planes were well displayed on an outcrop showing the contact between the felsic tuffs of the Deloro assemblage and the ultramafic flows of the Tisdale assemblage. At the map scale, the contact between those two assemblages that was interpreted from aeromagnetic data appears to reflect this folding event. F_3 folds and kink bands associated with this episode of deformation were mapped all across the area.

Major north-south faults in the area are mostly interpreted from abrupt lithological variations and with the help of geophysical patterns because of the lack of exposure. Among these structures, the Mattagami River fault represents a major break in the lithologies but its nature is poorly understood because there are very few outcrops at or near the interpreted break. It is hoped that petrography will help to define the main characteristics of the Mattagami River fault and related breaks.

Detailed description and interpretation of the relationship between the different episodes of deformation in the area, especially along the Porcupine-Destor deformation zone is the subject of a B.Sc. thesis for which data was gathered within this project. Dinel and Benn (this volume) present the preliminary results and the thesis is expected by May 2001.

MINERALIZATION

Two past producing gold mines in the area are located along the Porcupine-Destor deformation zone, in eastern and central Ogden Township. They are the Naybob (Kenilworth) and the Desantis mines. There are no mines currently in operation in the map area. However, St-Andrew Goldfields Ltd have recently announced a joint venture agreement with Holmer Gold Mines Ltd. for the potential development of the Holmer Gold Property in Bristol Township (from Web site www.standrewgold.com - Sept. 2000).

The Holmer Gold Property is located at the contact between the mafic volcanic rocks of the Kidd–Munro assemblage and the metasedimentary rocks of the Porcupine assemblage, in a shear zone believed by some to be the extension of the Porcupine-Destor deformation zone. Effects of the three episodes of deformation described above are very well expressed on the surface area of the Holmer Gold Property along with the very intense carbonate alteration.

There are other gold prospects currently being explored by companies along the Porcupine-Destor deformation zone and similarly trending deformation zones in the map area. A porphyry body in eastern Bristol Township is under investigation by Cameco Gold Inc. The potential similarities with the Pearl Lake porphyry which is in close relationship with major gold mines of the Timmins area brings a great interest for gold exploration in the Bristol Township porphyry. Other gold prospects include areas near the old Desantis and Naybob (Kenilworth) mines and along the Allerston shear zone.

DISCUSSION AND CONCLUSIONS

The relationship between the various lithologies from the volcanic Deloro, Kidd-Munro and Tisdale assemblages and the sedimentary Porcupine assemblage are very complex and difficult to define in part because of the lack of exposure. The superimposition of multiple phases of deformation including both north-south and east-west compression also adds an element of complexity. Recent exposure by exploration work along with diamond drilling is now starting to reveal newly defined folding patterns between the ultramafic and mafic volcanic rocks of the Tisdale assemblage and the felsic and intermediate volcanic rocks of the Deloro. Similar newly defined structures exist between the volcanic rocks of the Kidd-Munro assemblage and the sediments of the Porcupine assemblage. These patterns are very important in the understanding of the nature of the contacts in relationship to the location and effects of the gold-deposit associated deformation zones.

Further work will include compilation of data provided by companies and from assessment files and major and trace element geochemistry on both volcanic and intrusive lithologies. Intense petrographic study will be oriented toward description of the various lithologies and the analysis of the deformation affecting them. It is hoped that the continuation of this project with the collaboration of companies and prospectors will continue to bring greater understanding to this complex yet very interesting area with high mineral potential.

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5. Project Unit 97-013. Continuing Structural Investigations of Gold Mineralization along the Porcupine–Destor Deformation Zone in the Harker–Holloway Gold Camp, Abitibi Greenstone Belt

B. Luinstra

Ottawa–Carleton Geoscience Centre and the University of Ottawa, Department of Earth Sciences, 140 Louis Pasteur Priv., Ottawa, On, K1N 6N5. Bluins@science.uottawa.ca

INTRODUCTION

Structural investigations continued on the Porcupine–Destor deformation zone within the Harker–Holloway gold camp as part of a collaborative study involving the University of Ottawa, the Ontario Geological Survey, Battle Mountain Canada Ltd., and Barrick Gold Corp. Primary field work, completed in the field seasons of 1997–1999, concentrated on underground and surface mapping and structural analysis of the Holloway and Holt–McDermott mines, operated by Battle Mountain Canada Ltd., and Barrick Gold Corp., respectively (Luinstra and Benn 1997, 1999a, 1999b). Additional work completed over the winter season contrasted mineralization styles of the main ore zones of the two deposits (the Lightning Zone at Holloway and the South Zone at Holt–McDermott) petrographically and utilizing the Scanning Electron Microscope (SEM).

PETROGRAPHIC AND SEM EXAMINATION OF PYRITE MINERALIZATION

Gold mineralization in the Holloway and Holt–McDermott mines is associated with albitic alteration and pyrite mineralization. Fifteen samples of ore material from the South Zone ore body at the Holt–McDermott Mine and 34 samples from the Lightning Zone at the Holloway Mine were cut and polished for petrographic examination, carried out over the winter at the University of Ottawa. Representative samples were also examined by SEM at Carleton University in Ottawa. The goal of this portion of the study was to describe pyrite and gold mineralization styles for the two deposits and correlate this data with field observations and timing relationships as described by Luinstra and Benn (1997, 1999a, 1999b).

There is only one discernable style of pyrite mineralization at the Holt–McDermott Mine. These pyrites occur as extremely fine-grained crystals disseminated throughout mineralized rocks with an average grain size of less than 150 µm. Holt–McDermott pyrites have euhedral crystal forms, often perfectly cubic where unfractured by subsequent deformation. SEM examination of these pyrites show them to be both optically and chemically homogenous, with no apparent zoning. Figure 5.1A shows an SEM photomicrograph of a typical, unzoned Holt–McDermott pyrite. No gold was encountered in either petrographic or SEM analysis of Holt–McDermott samples.

A minimum of two pyrite mineralizing events has been documented in the Lightning Zone of the Holloway Mine (Luinstra and Benn, 1997, 1999a, 1999b). The first pyrite event is defined by small (<150 µm), euhedral pyrite grains that are disseminated throughout mineralized rocks. These pyrite grains are commonly found within interstices of albite clusters that are spatially associated with small grey, translucent quartz + albite veinlets and a pervasive albite alteration. Based on petrographic examination, it was theorized that these pyrite grains were coeval with the pyrite of the Holt–McDermott Mine's South Zone, largely based on their similar habits, euhedral crystal forms and average grain size. However, SEM examination revealed that the Holloway pyrite grains were in fact both optically and chemically zoned. These pyrite grains typically exhibit a simple, discrete, zoning pattern with As-poor cores and As-rich rims (Figure 5.1B).

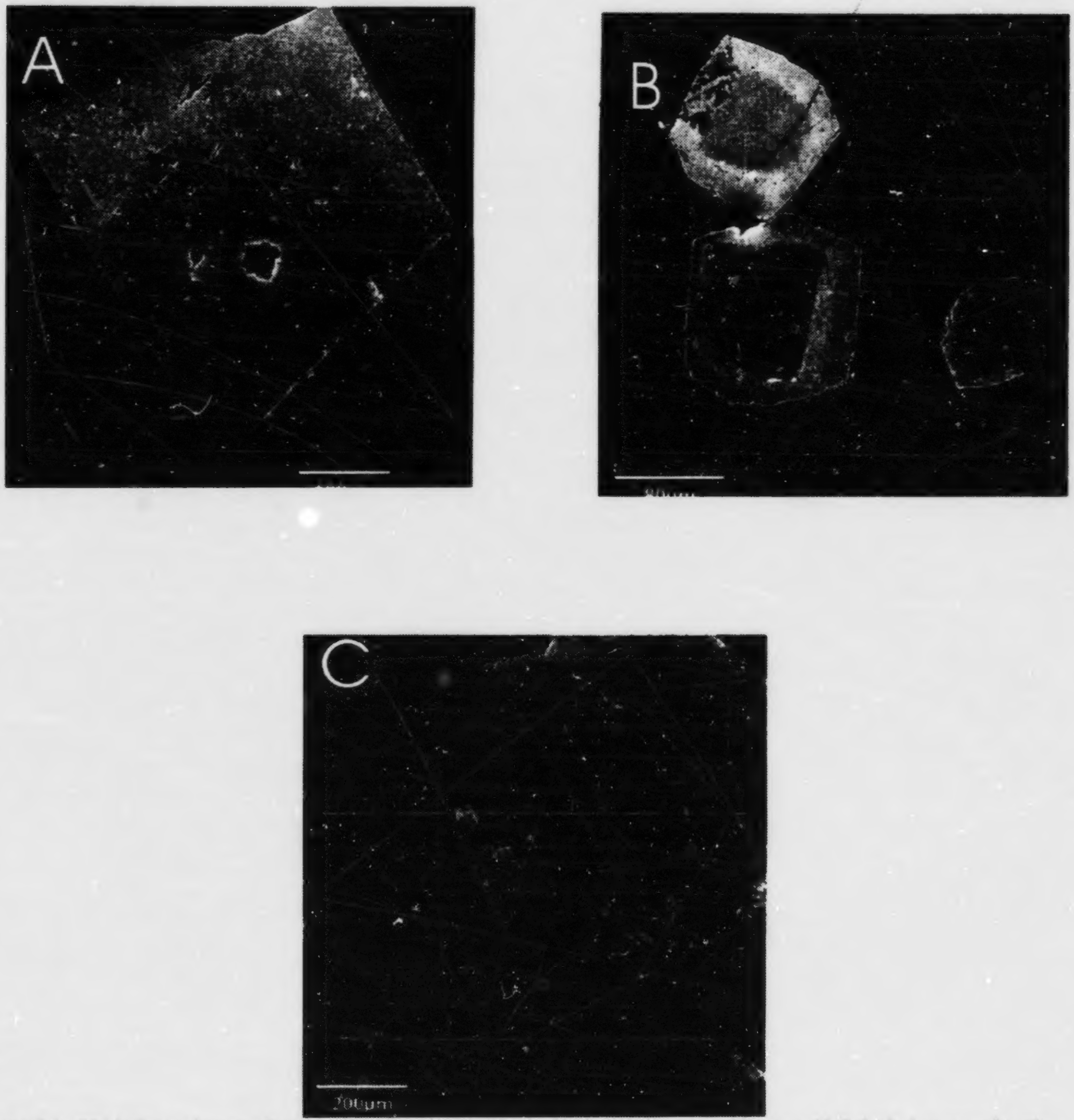

Figure 5.1. SEM photomicrographs of pyrite mineralization in the Harker-Holloway gold camp. **A)** Euhedral, unzoned pyrite from the South Zone at Holt-McDermott Mine. Scale bar is 100 µm. **B)** Euhedral pyrites with arsenic-rich rims from the Lightning Zone at the Holloway Mine. Scale bar is 80 µm. **C)** Arsenic-rich (light colour) and arsenic-poor pyrite from the Lightning Zone at the Holloway Mine. Scale bar is 200 µm.

A second pyrite mineralization at the Holloway Mine has been shown to postdate the earlier pyrite mineralizing event (Luinstra and Benn, 1999a). This mineralization is defined by large (>1mm) anhedral pyrite that are most commonly found within the Lightning Zone as well as within alteration haloes away from the Lightning Zone. These pyrite grains are often clustered on the edges of the quartz + carbonate veins and are also associated with increased Au and As values. SEM examination of these pyrites showed them to be aggregates of both As-rich, and As-poor pyrite, as shown in Figure 5.1C.

At the Holloway Mine, early pyrite record a sharp transition from arsenic-poor to arsenic-rich mineralizing fluids. A second remobilization of mineralizing fluids likely led to the formation of the larger aggregates of pyrite. This order of events is consistent with observed field data reported in Luinstra and Benn (1997, 1999a) in which disseminated, small, and euhedral pyrite mineralization is associated with early albitic alteration, and clustered, larger, and anhedral pyrite mineralization is associated with crosscutting carbonate + sericite alteration.

In contrast, pyrite mineralization within the South Zone of the Holt–McDermott Mine is unzoned and uniform throughout. Clearly, pyrite mineralization at the Holt–McDermott Mine records a much simpler sequence of mineralizing events.

FUTURE WORK

Previous work in the Harker–Holloway gold camp has led to the formation of a model in which gold mineralization in the area is part of a single large hydrothermal system (Luinstra and Benn 1999, 1999b; Robert 1997) largely based on the similarity of alteration styles and timing of mineralization with respect to regional structures. Preliminary petrographic and SEM examination of pyrite mineralization has revealed significant differences in mineralization styles. This suggests that two or more mineralizing systems are present in this area, an early arsenic-poor system and a second arsenic-rich system. SEM detection limits do not allow for accurate analysis of gold concentrations within pyrite. Additional analysis using Secondary Ion Mass Spectrometry (SIMS) technology is planned for the fall, which will provide accurate restraints on gold concentrations within pyrites. Additionally, samples of the Holt–McDermott Mine's South Zone were collected for whole rock geochemical analysis. This data will be treated using a mass balance approach in order to compare the chemistry of the altering fluids with those of the Holloway Mine (Ropchan 2000).

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6. Project Unit 98-15. Lithogeochemistry of the Shining Tree Area

H. S. Oliver[1], D. J. Hughes[1], R. P. Hall[1], G. W. Johns[2]

[1]University of Portsmouth, Portsmouth, Hants, UK
[2]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Greenstone belts are currently being researched for two reasons: 1) they provide one of the few windows to Early Precambrian crustal processes, tectonics and magmatism (Windley 1995; Hall and Hughes 1993; Condie 1997), and 2) a high percentage of the world's economically important metals are found within greenstone belts (Colvine et al. 1988). The principal focus of this study is the ca. 2.7 Ga Shining Tree greenstone belt, 120 km north of Sudbury. This belt and enveloping granitoids are part of the Abitibi Subprovince, Superior Province, northeast Ontario. Present work is to use mapping (Johns 1999b, 2000) in conjunction with geochemistry provided in this project (Oliver et al. 1998, 1999a, 1999b, this article) to constrain lithostratigraphic development, petrogenesis, tectonic evolution and tectonomagmatic provenance of the greenstone belt. The study sheds light on the debate concerning whether greenstone belts developed as a stratigraphic succession in place (ensialic development) or as a series of separate, tectonically juxtaposed unrelated (exotic) terranes (Ayres et al. 1985).

GEOLOGICAL SETTING OF THE SHINING TREE GREENSTONE BELT

The Shining Tree area is in the southern portion of the Abitibi Subprovince and has generally been considered part of the Abitibi greenstone belt (e.g., Ayer 1999). It is bounded by latitudes of 47°29′30″ to 47°45′30″ north and longitudes of 80°55′00″ to 81°27′30″ west. It is 120 km north of Sudbury.

The supracrustal rocks in the Shining Tree area have been divided into the Pacaud, Deloro, Kidd–Munro, Tisdale and Timiskaming assemblages (Figure 6.1) in keeping with the rest of the Abitibi greenstone belt (Ayer 1999; Ayer et al. 1999; Johns 1999b; Oliver et al. 1999b). Assigning the supracrustal rocks to assemblages was achieved by comparison of lithostratigraphy, geochemical composition and age of the rocks, with supracrustal rocks already classified in the Abitibi greenstone belt. The ~2687 Ma Timiskaming assemblage is separated from the older assemblages (>2.7 Ga) by an unconformity. The Timiskaming assemblage is also composed of a considerably different array of rocks than the older supracrustal rocks so it will be described separately. The geological setting and supracrustal rocks of the Shining Tree area are described in further detail in Johns and Amelin (1999) and Johns (1999b). Due to all the rocks in the Shining Tree greenstone belt being metamorphosed, the "meta" prefix is not used in this report from this point on.

2750 Ma to 2700 Ma Metavolcanic Assemblages

The Pacaud, Deloro, Kidd–Munro and Tisdale assemblages are dominated by volcanic supracrustal rocks, which were formed before the first phase of deformation. Felsic volcanic units close to the

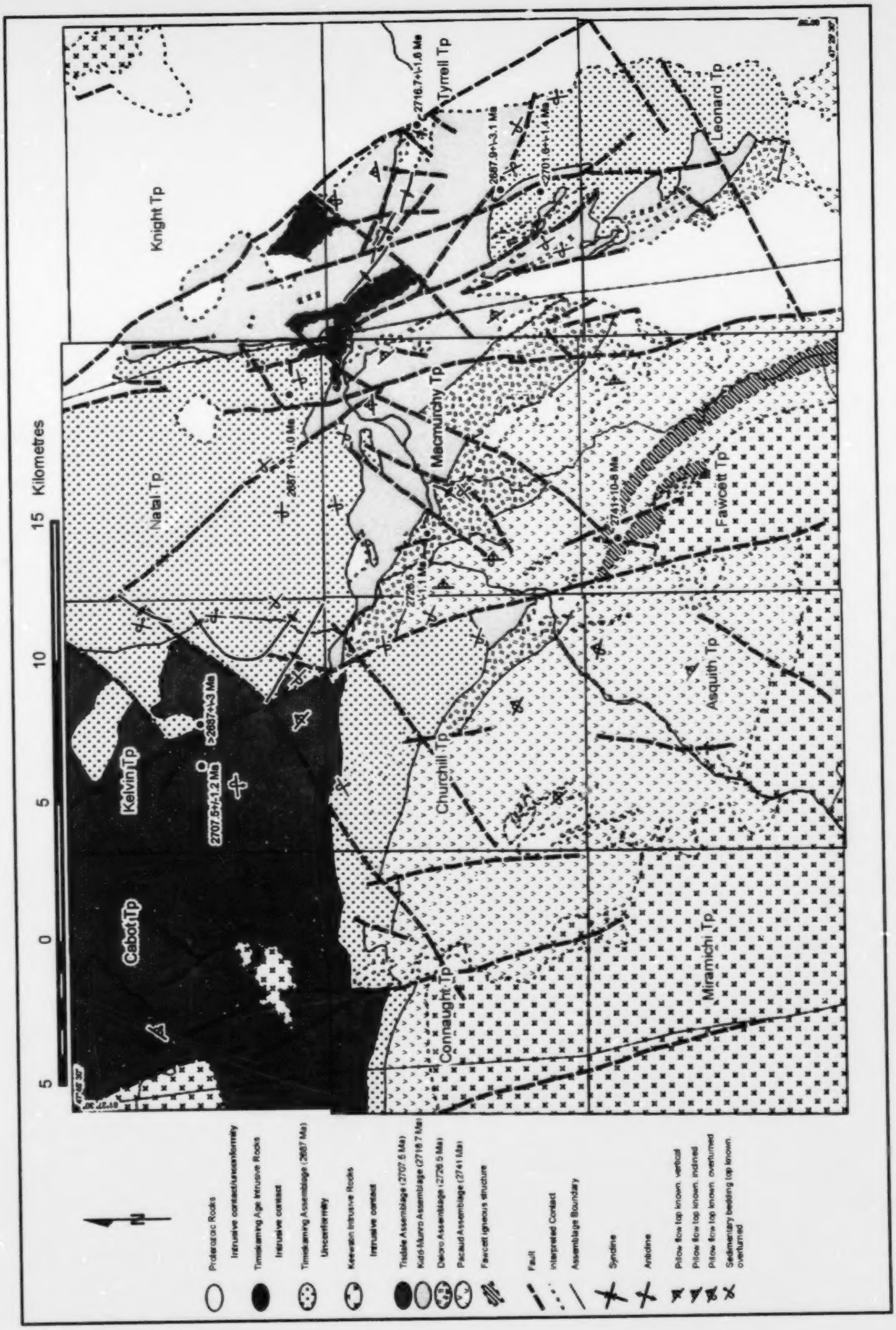

Figure 6.1. The lithostratigraphic assemblages of the Shining Tree area.

presumed tops of the assemblages in the Shining Tree area have been dated; zircons were extracted from the rock and then dated using the uranium-lead radioactive decay series (Johns and Amelin 1999). Ages of the pre-deformational assemblages are given in Tables 6.1 and 6.2. The ages of the older three assemblages (Pacaud, Deloro and Kidd–Munro) indicate that the greenstone belt youngs to the northeast (Figure 6.1). The Pacaud assemblage is mainly composed of massive and pillowed basalts and is associated with minor spinifex or cumulate textured komatiites. The Deloro assemblage is dominated by felsic volcanic rocks and is capped in many places by chemical sediments, seen as banded chert and jasper. The Kidd–Munro assemblage is a varied assemblage dominated by tholeiitic basalts and komatiites, with minor felsic volcanic rocks, and the Tisdale assemblage comprises mafic flows and intermediate to felsic pyroclastics and/or volcaniclastics (Johns 1999a).

Table 6.1. Ages of assemblages present in the Shining Tree area as defined in the Abitibi greenstone belt (Ayer et al. 1999).

Assemblage	Age	Lithological description
Timiskaming	2677 – 2686 Ma	Calc-alkaline volcaniclastics and epiclastics, alkaline basalt flows, intrusive stocks sometimes associated with gold deposits.
Tisdale	2710 – 2702 Ma	Tholeiitic – komatiitic volcanics, calc-alkaline intermediate – felsic pyroclastics.
Kidd-Munro	2717 – 2712 Ma	Tholeiitic – komatiitic volcanics, calc-alkaline intermediate – felsic pyroclastics.
Deloro	2730 – 2725 Ma	Mafic – felsic calc-alkaline volcanics, capped by regional chemical sediments. No tholeiites.
Pacaud	2745 – 2740 Ma	Calc-alkaline and tholeiitic volcanics.

Table 6.2. Ages of pre-deformational assemblages within the Shining Tree belt, the sample locations and the nature of the rock sampled.

Assemblage / Group	Age	Location	Lithological description
Tisdale	2707.5 ± 1.2 Ma	Kelvin Township	Andesitic block and ash flow
Kidd-Munro	2716 ± 1.6 Ma	Porphyry Lake, Knight Township	Rhyolitic tuff below chert horizon
Deloro	2726 ± 1.6 Ma	Bigfour Lake, Macmurchy Township	Rhyolitic massive flow, with clastics interbedded with minor chert
Pacaud	2741 +10 –8 Ma	NW Fawcett Township	Sheared intermediate tuffs
Natal group	2687.1 ± 1.0 Ma	Barite Lake, Natal Township	Hornblende & feldspar phyric lava
Natal group	2687 ± 3.0 Ma	Kelvin Township	Sediment (detrital zircon)
Indian Lake group	2701.6 ± 1.4 Ma, 2740 ± 1.1 Ma	Indian Lake, Tyrrell Township	Sediment (detrital zircon)
Indian Lake group	2687.9 ± 3.1 Ma	Indian Lake, Tyrrell Township	Rhyolite

Data from Johns and Amelin (1999) and Ayer et al. (1999).

Timiskaming Supracrustal Rocks

The Miramichi and Togo batholiths envelop the Shining Tree area (Figure 6.1), but were intruded prior to deposition of the Timiskaming assemblage. Within the Abitibi greenstone belt and the Shining Tree area, clasts of large felsic intrusions are present in the Timiskaming sediments. Within the Shining Tree area the Timiskaming assemblage has been divided into two lithostratigraphically distinct groups, the Indian Lake group (ILG) in the south and east, and the Natal group (NG) in the north and the west (Johns and Amelin 1999; Johns 1999a). The Natal group comprises volcanic pyroclastic rocks and flows and associated volcaniclastic sediments. Zircons from these sequences have been dated using U/Pb at 2687 ± 3 Ma (Tables 6.1 and 6.2). The sediments of the Natal group formed by reworking of the pyroclastic rocks. The zircons present in the sedimentary rocks are detrital, and as they have the same age as the volcanic rocks, the only other source of this age of rock, they presumably come from reworked Timiskaming volcanics. Unconformities seen between the Natal group and the underlying Keewatin sequences (Johns 1996, 1997, 1999a; Johns and Amelin 1999), are evidence of a hiatus in volcanic activity. The predominantly volcanic facies of the group is found in southeast Natal Township and grades north and west into reworked pyroclastics, wackes and siltstones in Kelvin Township. The volcaniclastic rocks and associated pyroclastics are mainly tuffs, lapilli tuffs and tuff breccias. Timiskaming sediments are also located in a wide strip trending west across the northern portion of Connaught and Churchill townships (Carter 1987; Johns 1996, 1997 and 1999a; Johns and Amelin 1999) (Figure 6.1).

The sedimentary Indian Lake group (ILG) is composed of texturally immature quartzo-feldspathic arenites and wackes, with minor conglomerates and rare mudstones. This collection of lithologies is recognized throughout the Abitibi belt to be indicative of the Timiskaming assemblage (Ayer et al. 1999). The ILG has been dated using U/Pb of detrital zircons, to produce detrital ages of 2701.6 ± 1.4 Ma and 2740 ± 1.1 Ma (Ayer 1999; Johns and Amelin 1999). The zircon producing an age of 2740 ± 1.1 Ma may have been derived from the Pacaud volcanics; these are the only rocks in the area with a comparable age (2741 +10 –8 Ma). Confirmation of a Timiskaming age for the ILG is provided by a calc-alkaline felsic flow dated at 2687 ± 3 Ma (Ayer et al. 1999) (Tables 6.1 and 6.2).

The volcanic rocks found towards the base of the Natal group are feldspar and amphibole and/or pyroxene phyric calc-alkalic and alkalic flows and pyroclastic rocks. These grade towards the northwest into reworked volcaniclastics, coarse grained in the southeast, and fine grained to the northwest of the Natal group. Syenite and monzonite stocks are located in the east of the studied area. These are associated with the volcanic rocks in the Natal group (Johns 1997, 1999a; Johns and Amelin 1999).

Metamorphism and Structure

The metamorphic grade throughout most of the Shining Tree area is mid to low greenschist facies (Oliver et al. 1999a, 1999b). Amygdules are filled with chlorite, carbonate or quartz and there is extensive saussuritization of feldspars in mafic flows and intrusions. Feldspars within felsic volcanics are commonly sericitized, a feature which is possibly deuteric in origin. Locally, the levels of metamorphism and deformation are low enough to preserve delicate volcanic textures. However, adjacent to the felsic intrusions, such as the Miramichi and Togo batholiths, the metamorphic grade reaches amphibolite facies where the mineralogy of the rocks is dominated by hornblende (Oliver et al. 1999a, 1999b).

There are two main phases of deformation and associated metamorphism in the Shining Tree area (Oliver et al. 1999a, 1999b) with rocks older than 2.7 Ga having undergone two periods of deformation. In some places a crenulation cleavage is evident and quartz crystals have strained extinction. There are multiple deformation zones in the older volcanic rocks in which gold has been found, especially in

Macmurchy and Tyrrell townships (Figure 6.1) (Johns 1996, 1997 and 1999a). The Timiskaming assemblage has undergone a single period of deformation and is metamorphosed to a lesser degree than the older volcanic rocks, igneous zoning in primary hornblende phenocrysts commonly being preserved (Oliver et al. 1999a, 1999b). The Timiskaming assemblage was formed between the two deformation events and lies unconformably above the pre-deformational volcanics.

The Kenoran Orogeny was a collisional event produced by accretion of disparate Archean fragments to form the Superior Province. Deformation was most intense between 2720 and 2660 Ma (Thurston 1991). This orogeny encompasses both the deformation events seen in the Shining Tree area.

PETROLOGY OF THE IGNEOUS ROCKS OF THE SHINING TREE GREENSTONE BELT

Introduction

The Shining Tree area contains a large proportion of basaltic flows and associated komatiites. These rocks are being used to investigate the petrogenesis of the greenstone belt, the tectonomagmatic environment in which the rocks formed, and the nature of the Archean mantle below the Shining Tree area. Komatiites, which are rarely seen in post-Archean rocks (Kerr et al. 1996), can provide a revealing view of the mantle, as they are among the most primitive igneous rocks on the Earth. Supposing that they evolved directly from the mantle, they can be used to study the nature of their source.

Samples were collected by H.S. Oliver and G.W. Johns from 1997 to 1999, with preliminary sampling by Johns in 1996. In 1997, the sampling was concentrated along Highway 560 (Figure 6.1). A far more extensive spatial distribution of samples was achieved in 1998 and 1999. The present coverage extends into all but the relatively inaccessible Connaught Township. More than 380 samples have been taken from the Keewatin assemblages, more than 70 from the Timiskaming volcaniclastics, and 50 Timiskaming sediments.

Until recently, the mafic rocks comprising parts of a greenstone belt were often treated as a single unit. It was not understood that they have different geochemical signatures, and it was thought they could not readily be geochemically related to modern geodynamic environments (Condie 1976). However, in the last decade, data revealed that the mafic volcanic rocks can be subdivided into discrete assemblages (Thurston and Chivers 1990). The assemblage concept allowed packages defined on lithostratigraphic grounds to be identified and interpreted using geochemical characteristics, principally based on trace element distributions (Jackson, Fyon and Corfu 1994; Tomlinson, Hughes and Thurston 1996a). Major element plots are useful for discriminating between rock types and demonstrating mantle processes important in the formation of greenstone belts. However, as almost all of the major elements used have been proved to be mobile to some degree, they have to be interpreted with great care (Rollinson 1993). As all of the rocks in Archean greenstone belts are metamorphosed and/or altered to varying degrees and therefore have unreliable major element concentrations, immobile elements are used for petrogenetic modelling, or to confirm initial interpretations based on major elements. The HFSE (Th, Nb, Ta, Zr, Hf, Y and Ti) are less mobile than the light rare earth elements (LREE) (Jenner 1996). These, together with the medium rare earth elements (MREE) and heavy rare earth elements (HREE), and the major element oxide Al_2O_3 (also thought to be relatively immobile in Precambrian tholeiites and komatiites) are best used for trace element systematics (Kerrich and Wyman 1996). The trace element geochemistry of volcanic rocks has been shown to be a useful exploration filter, particularly for volcanogenic massive sulphide (VMS) deposits (Lesher et al. 1986; Kerrich and Wyman 1996). For example, geochemical data can identify alkaline volcanic rocks associated with Neoarchean pull-apart basins which have distinct economic mineralization (e.g., shear zone gold) associated with them (Thurston and Chivers 1990 and references therein).

Tomlinson et al. (1995) demonstrated that the Lumby Lake greenstone belt in the (3.1 to 2.5 Ga) Wabigoon Subprovince (western Ontario) can be divided into discrete packages on the basis of lithostratigraphic mapping and trace element characterization. The same is true of the Beardmore–Geraldton greenstone belt (Tomlinson et al. 1996b). Incompatible element geochemistry can be used to assign metavolcanic sequences to a likely tectono-magmatic setting and source region (Pearce 1996). For example, Tomlinson et al. (1996b) found that the Beardmore–Geraldton greenstone belt is composed of three packages representing oceanic, arc and back-arc crust which accreted prior to collision with the Wabigoon arc.

Analytical Techniques

To prepare for geochemical analysis the samples were first cleaned, crushed, then powdered in a tungsten carbide Tema ring mill. The samples were analyzed for major elements and 11 trace elements using a Philips 1480 X-ray fluorescence (XRF) spectrometer with a rhodium tube at the University of Portsmouth geochemical laboratories in the School of Earth, Environmental and Physical Sciences. Pressed powder pellets were used to analyze trace elements and glass fusion discs prepared according to the method of Norish and Hutton (1969) for major element analysis. When compared to international assessment, trial samples are within acceptable accuracy and precision limits (cf. Tomlinson 1996), with precision of less than 1 wt % for major elements from the standard analysis. Trace elements including the rare earth elements (REE) were also analyzed using a Sciex-Perkin-Elmer ELAN-5000 Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) at the Geosciences Laboratory at the Ministry of Northern Development and Mines, Sudbury, Ontario.

PRE-DEFORMATIONAL (>2.7 GA) VOLCANICS

Within the Shining Tree area, the rocks have a large range of geochemical compositions. Rocks from the assemblages older than 2.7 Ga include komatiites and tholeiitic basalts and are discussed in the following section.

Komatiites

In the Pacaud assemblage, komatiitic flows are confined to a small area close to the top of the sequence. In the northeast part of the Shining Tree area, komatiite flows interbedded with tholeiitic basalts cover an extensive area towards the top of the Kidd–Munro assemblage. The komatiitic flows demonstrate macro- and micro-spinifex textures, polysuturing and brecciation. Thin dunitic cumulate horizons also occur in flows at several horizons in the Kidd–Munro assemblage. These komatiitic flows tend to be black and talcose unless silicified or otherwise altered, in which case they weather to a pale grey colour (Johns 1996, 1997; Johns and Amelin 1999). The komatiites are commonly carbonitized and in a few locations in the Pacaud assemblage they contain abundant fuchsite, imparting a strong green colour to the rock. This alteration is also associated with silicification, but the HFSE, REE and some of the major element oxides such as Al_2O_3 and TiO_2 appear to be unaffected. The komatiites from the Pacaud assemblage all have high degrees of carbonatization, which can be identified on a microscopic level, some have a schistose texture and none have their primary texture preserved. All of the komatiites from the Pacaud assemblage are petrographically different from the Kidd–Munro (KM) komatiites.

A significant difference can be seen in the geochemistry between the komatiites of the Pacaud and the Kidd–Munro assemblages. With slightly depleted to unfractionated primitive-mantle normalized multi-element distributions ($(La/Sm)_N = 2.12 - 0.53$, $(Gd/Yb)_N = 1.10 - 0.93$) and high Al ($Al_2O_3/TiO_2 = 23.7 - 13.7$) (Figures 6.2a and 6.2b), the KM komatiites are very similar to the aluminum-undepleted Tisdale-type komatiites in the Abitibi greenstone belt (Xie and Kerrich 1994). The KM komatiites include both peridotitic and basaltic types (MgO = 40.7 – 13.0 wt %), which could be products of fractional crystallization and crystal accumulation. Some of these KM komatiites are LREE enriched as well as depleted in Nb, perhaps indicative of crustal contamination. The komatiites of the Pacaud assemblage have slightly depleted LREE ($(La/Sm)_N = 0.56 - 0.43$, $(Gd/Yb)_N = 0.80 - 0.60$) and higher Al ($Al_2O_3/TiO_2 = 28.09 - 21.47$) (Figures 6.2b and 6.3). These ratios are similar to the Munro-type komatiites also found in the Abitibi greenstone belt (Xie and Kerrich 1994), but are enriched in Al, making them more similar to the Gorgona komatiites (Arndt et al. 1997). The komatiites of the Pacaud assemblage are all peridotitic (MgO = 28.8 – 19.9 wt %). Most Neoarchean komatiites are aluminum-undepleted, whereas most komatiites older than ~3 Ga are aluminum depleted. The Kidd–Munro komatiites are aluminum-undepleted and are similar to most Neoarchean komatiites, they have average Al/Ti ratios which are a function of HFSE enrichment as well as aluminum depletion (Figure 6.3). The Pacaud komatiites are similar to the Gorgona komatiites and show HREE enrichment (low Gd/Yb ratio) as well as above average Al/Ti ratios, indicating Al enrichment (Figure 6.3) (Tomlinson et al. 1996c). Compare results with Sproule (this volume).

Tholeiitic Volcanic Flows

Basalts and basaltic andesites in the Shining Tree area occur largely as pillowed or massive flows, but also include variolitic and spherulitic flows, feldspar phyric flows and amygdaloidal flows. The pillows are commonly well preserved and are of the order of 1 to 2 m long and 0.5 m thick, with fine-grained margins, and a minor inter-pillow hyaloclastite. Alteration includes late carbonate veins and silicification.

The tholeiitic basalts have been examined in terms of the assemblages within which they are located, but there is little geochemical difference between them (Figure 6.4). All of the basaltic units have unfractionated primitive-mantle normalized multi-element distributions (Figure 6.2d-g). The Pacaud tholeiites have unfractionated REE ratios ($(La/Yb)_N = 1.51 - 0.90$), the Kidd–Munro assemblage tholeiites have $(La/Yb)_N = 1.57 - 0.79$, and the Tisdale assemblage tholeiites have $(La/Yb)_N = 1.46 - 0.64$. Due to the similarities between the tholeiitic basalts from the assemblages, the following is collated data from basalts of all the assemblages. These rocks have unfractionated primitive-mantle normalized multi-element distributions ($(La/Sm)_N = 1.25 - 0.92$; $(Gd/Lu)_N = 1.41 - 0.93$). They are slightly depleted in the HFSE, Ti ($(Ti/Gd)_N = 0.94 - 0.78$) and Nb ($(Nb/La)_N = 0.78 - 0.69$ (Oliver et al. 1999a)).

Partial melting modelling of the tholeiitic basalts shows a tholeiite field which encompasses the following sectors of Figure 6.4: high degrees of partial melting in an enriched spinel lherzolite source, high degrees of partial melting in an enriched garnet lherzolite, and low degrees of partial melting in a depleted spinel lherzolite source.

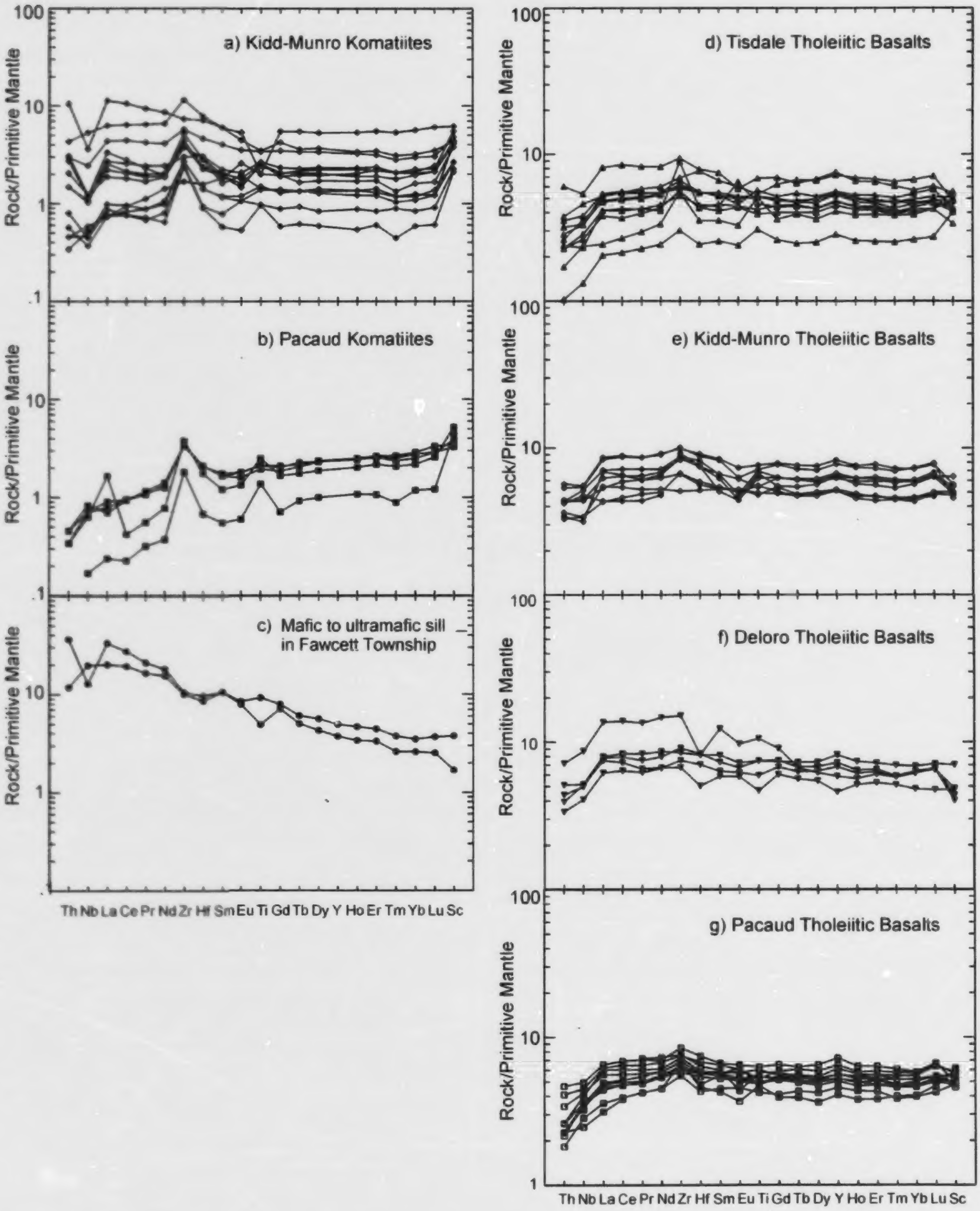

Figure 6.2. Mantle normalized multi-element plots of ultramfic rocks from the Kidd–Munro and Pacaud assemblages and the mafic to ultramafic sill in Fawcett Township and the tholeiitic basalts from the Tisdale, Kidd–Munro and Pacaud assemblages.

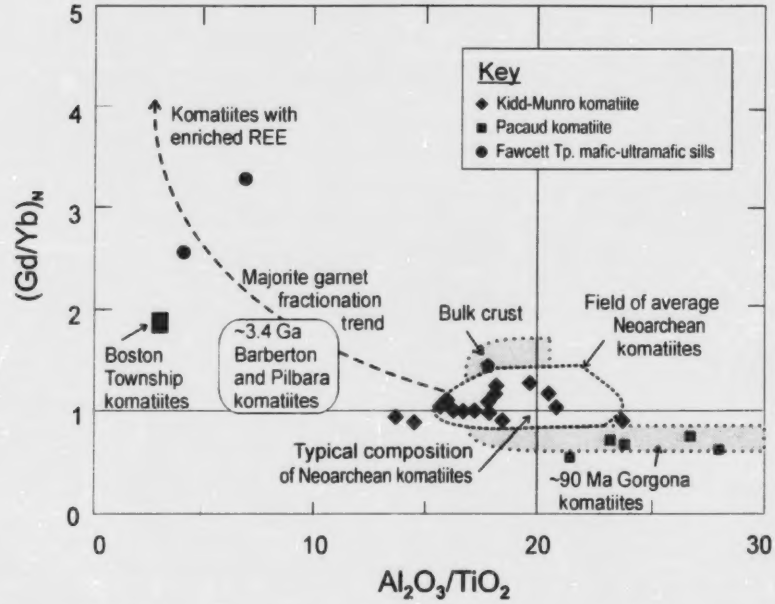

Figure 6.3. Most Neoarchean komatiites are Al undepleted whereas most komatiites older than ≈3 Ga are Al depleted. The Kidd–Munro komatiites are Al undepleted and are similar to most Neoarchean komatiites. The have average Al/Ti ratios which are a function of HFSE enrichment as well as Al depletion. The Pacaud komatiites are similar to the Gorgona komatiites and show HREE enrichment (low Gd/Yb ratio), as well as above average Al/Ti ratios showing Al enrichment. Ultramafic rocks from the the mafic to ultramafic sill in Fawcett Township are similar to komatiites from Boston Township in the Abitibi greenstone belt and display very low Al/Ti ratios, possibly due to elevated TiO_2 concentrations. These ultramafic samples also show HREE depletion (high GD/Yb ratios) (*modified from* Tomlinson et al. 1996c).

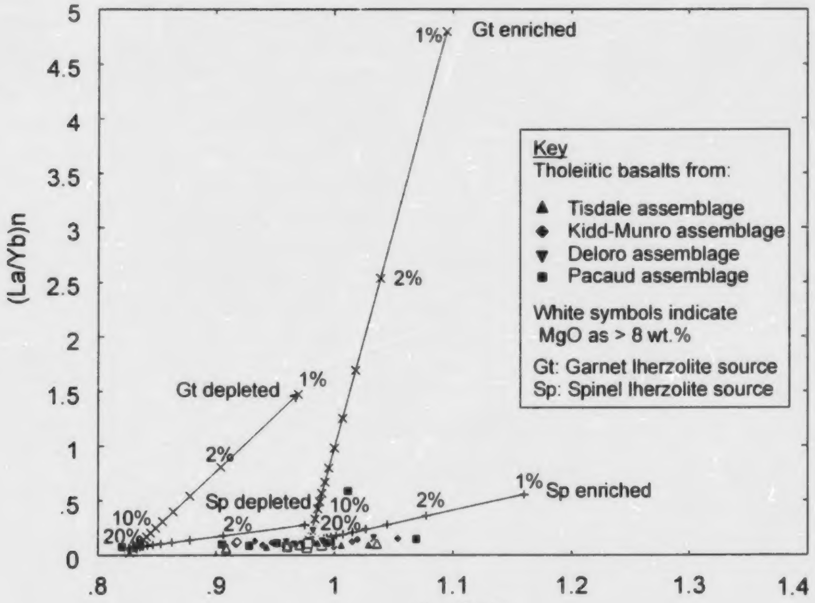

Figure 6.4. Partial melting model of tholeiitic basalts from multiple assemblages. Individual assemblages can not be subdivided using this diagram and all are high MgO basalts. (*modified from* Hards et al. 1995).

Mafic to Ultramafic Sill

Within Fawcett Township is a mafic to ultramafic sill, with a composition ranging from mafic to ultramafic. The sill can be traced using an airborne magnetic survey, as a long, linear feature spanning Fawcett Township. It appears to be concordant with the volcanic rocks of the Pacaud assemblage. The sill is terminated by the Granite Lake Fault near the western margin of Fawcett Township. This sill has been interpreted as komatiitic flows (Carter 1977) and more recently as a thin sill due to its placement within felsic flows (Johns and Amelin 1999).

The rocks from this structure are pyroxene-phyric, coarse grained and have a range in MgO from 19 to 10 wt %. Ultramafic samples from the sill are similar to aluminum-depleted (with respect to average Neoarchean komatiites) komatiites from Boston Township in the Abitibi greenstone belt, displaying very low Al/Ti ratios, possibly due to elevated TiO_2 concentrations (Figure 6.3) (Tomlinson et al. 1996c). They have ca. 45.9 wt % SiO_2 and 19.4 –14.5 wt % MgO. The ultramafic samples from the structure are characterized by HREE depletion (Figures 6.2c and 6.3), (high $(Gd/Yb)_N$ = 3.30 –2.73) and low Al (Al_2O_3/TiO_2 = 7.42 – 4.53; Al_2O_3 = 7.79 – 6.60 wt %; CaO/Al_2O_3 = 1.4 – 1.3). They are depleted in Nb, Hf and Zr, with Nb/Nb*, Hf/Hf* and Zr/Zr* = 0.42 – 1.00, ~0.66 and ~0.74 respectively, where Nb* is the average value between La and Ce, Hf* is defined in the same way as Nb*, but relative to Nd and Sm, and Zr* relative to Nd and Sm. The ultramafic samples of the sill have low Cr (Cr = 968 – 1115 ppm) relative to extrusive komatiites of comparable MgO values from the Shining Tree area (Cr = 1670 – 4114). Two samples from the sill are high magnesium-basalts with 10.3 and 10.1 wt % MgO. This suggests that the intrusion may be fractionated or layered. The structure is the only example of light rare earth element-enriched and heavy rare earth element depleted ultramafic rocks in the greenstone belt (Figure 6.2a-c).

DISCUSSION

Magmatism in the Shining Tree area is complex and does not constitute a simple evolutionary magmatic sequence. The division of the Shining Tree greenstone belt into 5 assemblages has been partially confirmed by the differences in chemistry between the komatiites associated with the Pacaud and Kidd–Munro assemblages. The komatiites from the Pacaud assemblage have higher Al than the younger komatiites in the Shining Tree area, to the extent that they may be enriched in Al. This may have happened at the source, or during transport to the surface. The Pacaud komatiites are similar to Munro-type komatiites (Xie and Kerrich 1994) but have an even closer affinity with those found at Gorgona. The extrusive komatiite flows of the Kidd–Munro assemblage are Al undepleted and are similar to the Tisdale-type komatiites. These may be sourced from primitive mantle less than 300 km deep (Xie and Kerrich 1994). The enrichment in Th and light rare earth elements paired with a depletion in Nb suggests that some of the Kidd–Munro komatiites might be crustally contaminated, but further analysis and modelling is required to confirm this (Figure 6.2a). Arndt, Kerr and Tarney (1997) suggested that the depletion of LREE at Gorgona might be due to dynamic melting, whereby an early melt fraction that never erupted, removed the most incompatible elements from the core of the plume, thus creating LREE depletion in later magmas from that source. The Munro-type komatiites are thought to have originated at a depth greater than 700 km, in a source enriched with Mg-perovskite (Xie and Kerrich 1994). Further investigation should reveal the true petrogenesis of the Pacaud komatiites. An aluminum-depleted ultramafic to mafic intrusion in Fawcett Township is distinct from the extrusive komatiites (Figures 6.2 and 6.3) and is similar to komatiites from Boston Township (Abitibi Subprovince). The Boston Township komatiites are postulated to have a source 300 to 600 km deep in a majorite-depleted mantle (Xie and Kerrich 1994). Their incompatible element geochemistry suggests that the two groups of komatiites could not have evolved from each other by fractional crystallization. The creation of these komatiites must have involved differences in their sources, perhaps indicating their derivation from a heterogeneous plume, multiple plumes, or different depths of origin.

Tholeiitic basalts comprise the rest of the Pacaud assemblage, are dominant in the Kidd–Munro assemblage, and are also found within the Tisdale assemblage. They are high-iron and high-magnesium tholeiitic basalts. Trace element geochemistry results suggest that the majority of the tholeiites have geochemical characteristics similar to those of modern normal mid-ocean ridge basalts (N-MORB). It is not possible to distinguish geochemically between tholeiites from different assemblages. Partial melting modelling of the tholeiitic basalts indicates that the basalts could have been produced by the following: high degrees of partial melting in an enriched spinel lherzolite source, high degrees of partial melting in an enriched garnet lherzolite and low degrees of partial melting in a depleted spinel lherzolite source (Figure 6.4). Formation of the tholeiitic basalts within a garnet lherzolite source would be indicated on multi-element distribution patterns as depleted HREE, as garnet retains the HREE normally released into a melt. The mantle-normalized multi-element diagrams are unfractionated (Figure 6.2d-g), therefore the basalts must have formed at shallower depths in the spinel lherzolite zone. Tholeiitic basalts normally form from 10 to 30 % melting according to geochemical and experimental studies (Wilson 1989) and a low degree of partial melting gives rise to highly fractionated REE distributions, as the LREE are more incompatible than the HREE or MREE. The basalts examined here have slightly depleted LREE and unfractionated HREE; this distribution is almost completely unfractionated (Figure 6.2d-g). The remaining model for partial melting is then formation within an enriched or partially enriched spinel lherzolite at high degrees of partial melting (Figure 6.4). This enrichment could be due to two factors. The mantle at 2.7 Ga may not yet have become as depleted as it now is beneath modern spreading centres. However, it has been postulated (Oliver et al. 1999b) that the volcanics of the Shining Tree area may have formed in a back-arc basin setting; in this case the mantle may have been originally depleted, but then re-enriched by metasomatism below the volcanic arcs. Komatiites present in the Shining Tree area were formed by the adiabatic upwelling of enriched mantle plume material; this may also have partially enriched previously depleted mantle.

The majority of the volcanics within the Deloro assemblage have an intermediate to felsic composition and have a calc-alkalic arc signature characterized by prominent negative Nb, Ta and Ti anomalies (Oliver et al. 1999a). These groups clearly did not evolve one from the other, but came from two distinct magma sources.

The Timiskaming assemblage unconformably overlies the Keewatin sequences and comprises volcanic rocks which have an alkalic signature but which still retain the negative Nb and Ti anomalies characteristic of an arc-influenced tectonic environment (Wilson 1989). The sediments and volcaniclastics of the Timiskaming assemblage in Timmins and Kirkland Lake were formed in fault-bounded late-stage successor basins (Mueller and Donaldson 1992). To date, there is no evidence of the Natal group and Indian Lake group having been formed within fault-bounded basins.

The inter-layered tholeiitic basalts and associated komatiites of the Pacaud assemblage probably formed in an extensional marine basin, possibly with a plume influence. The basin then presumably closed as subduction was initiated and volcanic arcs developed to produce the Keewatin calc-alkaline volcanic rocks concentrated in the Deloro assemblage. The sequence then may have rifted to produce the Kidd–Munro assemblage, the komatiites possibly having been generated by a plume, while an arc source continued to produce the calc-alkaline volcanics that were dominant in the older Deloro assemblage. The Tisdale assemblage in the northwest of the Shining Tree area contains a variety of rock types from komatiites and tholeiites to calc-alkaline pyroclastic deposits and requires further investigation. The western part of the sequence was intruded by tonalitic plutons, before rifting produced the late-stage calc-alkalic and alkalic Timiskaming assemblage.

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7. Project Unit 00-043. Geology, Volcanology, Lithogeochemistry and Alteration Associated with Volcanogenic Base Metal Mineralization in the Big Four Lake Area, Shining Tree, Abitibi Greenstone Belt, Ontario

G. Leblanc[1], G.W. Johns[2], J. Ayer[2] and A.D. Fowler[1]

[1]Ottawa Carleton Geoscience Center and Department of Geology, University of Ottawa
[2]Precambrian Geoscience Section, Ontario Geological Survey

The Shining Tree area was mapped by the Ontario Geological Survey during the 1970s (Carter 1987). As a result of exploration activity in the area a reinterpretation of the area at the scale of 1:50 000 was initiated in 1996 (Johns 1996, 1997, 1999; Johns and Amelin 1999). The thesis area is located in the northwest part of Macmurchy Township in the Shining Tree area.

The objective of the research project, which forms Geneviève Leblanc's M.Sc. thesis is to describe and characterize the base metal and gold mineralization that exists in the area. During the field season KRL Resources Corporation, a Vancouver-based exploration company had an active exploration and drilling program in the area and generously made the drill core available to the senior author. Samples from outcrop and KRL Resources Corporation drill core of both mineralized and unmineralized rocks will be studied in thin section and analysed for major and trace elements in order to better understand their petrogenesis, and to determine the style of hydrothermal alteration and mineralization.

Detailed mapping (1:10 000) in the northwest part of Macmurchy Township and on an exploration grid established by KRL Resources Corporation was undertaken over 11 weeks during the summer of 2000. As part of this mapping project, 271 outcrops were observed and approximately 250 samples were taken. Of these, approximately 40 have been selected for major oxide and selected trace element geochemical analysis. The samples include specimens taken from 5 of 13 KRL drill holes where the base metal mineralization is well constrained. A poster highlighting the results of the research will be presented at the upcoming Northeastern Mines and Minerals Symposium in April 2001, as well as April 2002.

The major units observed form part of the Deloro assemblage that have been dated at 2726.5 ± 1.1 Ma (Johns and Amelin 1999). The major rock types encountered include a mafic metavolcanic unit in addition to two distinct units of metarhyolite. Based upon chemical analyses provided by KRL Resources Corporation, the mafic unit appears to be predominantly composed of tholeiitic, massive or pillowed flows, however brecciated facies were occasionally observed. They are typically fine grained but often contain 1 to 2 mm patches of fine-grained amphibole. Carbonate-filled amygdules, millimetre to centimetre in diameter, are apparent and the unit is chloritized and locally carbonatized.

The unit containing the base metal mineralization is termed the Red Dome rhyolite by KRL geologists and the Big Four Lake rhyolite by Johns and Amelin (1999). Preliminary analyses indicate that it is part of a calc-alkaline suite. It is mostly fine grained and massive and locally contains a brecciated possibly autoclastic facies. The unit most likely represents a felsic dome. This unit outcrops on the northwest part of the KRL grid. It is typically altered, and generally contains hematite, sericite, and, on occasion, epidote. Alteration intensifies near the Brunet copper occurrence. Veins containing chalcopyrite, malachite and hematite found locally crosscutting the rhyolite. Specular hematite is generally associated with pink calcite and can be found along Highway 560 near the bridge crossing the Montreal River. Red jasper chemical sediment separates the fine-grained Red Dome rhyolite from overlying mafic metavolcanic rocks.

A second felsic volcanic rock consists of a pyroclastic facies and is called the South rhyolite by KRL geologists. It is generally greenish in colour and composed of millimetre-size fragments of feldspar and locally 1 to 12 centimetre size clasts of pumice in a chloritic vitriclastic matrix. This matrix often has well-preserved perlitic textures. In places, the pumice appears to be flattened to fiamme, suggesting hot emplacement by pyroclastic flow mechanisms. This unit outcrops on the southeast part of the KRL grid. The South rhyolite is altered and contains both sericite and chlorite. Reworked volcaniclastic rocks are interbedded with the South rhyolite and contain graded beds and flame structures.

All of the above rocks are cut by north-striking, fine-grained, mafic dikes, some containing epidotized plagioclase phenocrysts less than 1 centimetre in size. These diabase dikes are magnetic and most likely belong to the Matachewan swarm.

Research during the upcoming fall and winter will involve the production of a geology map of the area, and detailed petrography will be done in order to characterize the igneous and metamorphic textures, the primary mineralogy of the rocks, where possible, and the alteration minerals. The mineralogy will be compared with the results of the geochemical analyses in order to further classify the rocks, their alteration and mineralogy. Future plans are to spend a minimum of several weeks in the area during the 2001 field season in order to verify the existing data and to expand the mapping to some new areas that include gold mineralization.

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8. Project Unit 99-026. Petrogenesis of Syenitic Magmatism Associated with Gold Mineralization Along the Destor–Porcupine Fault Zone Near Matheson, Ontario

L. Pigeon[1], **A.E. Lalonde**[1], **B. Berger**[2]

[1]Ottawa-Carleton Geoscience Centre, University of Ottawa, Ottawa, Ontario
[2]Precambrian Geoscience Section, Ontario Geological Survey

We describe the petrography, mineralogy and geochemistry of a suite of small intrusions of syenite and related rocks that are closely associated with gold mineralization in the Destor–Porcupine zone, near and east of Matheson, Ontario. The intrusions studied are from east to west, the Iris, Garrison, Emens Lake, Ludgate and Pangea (Figure 8.1).

The objectives of this study, which constitutes part of an M.Sc. project at the University of Ottawa are: 1) to determine the petrogenetic evolution and emplacement conditions of the intrusions, 2) to delineate the geochemical evolution of the suite, 3) to investigate the mineral chemistry of the principal ferromagnesian minerals in order to gain insight into the redox conditions that prevailed during crystallization, and 4) to characterize the postmagmatic alteration associated with these rocks.

In this paper, we summarize some of the salient geochemical features that are apparent at this early stage of the project. All the fieldwork was accomplished during the summer of 1999. A large amount of work has yet to be accomplished, primarily in the fields of petrography and mineral chemistry, before announcing any definitive interpretations. However, based on the available geochemical data, we can recognize certain common features among some of the intrusions, and group these together for the

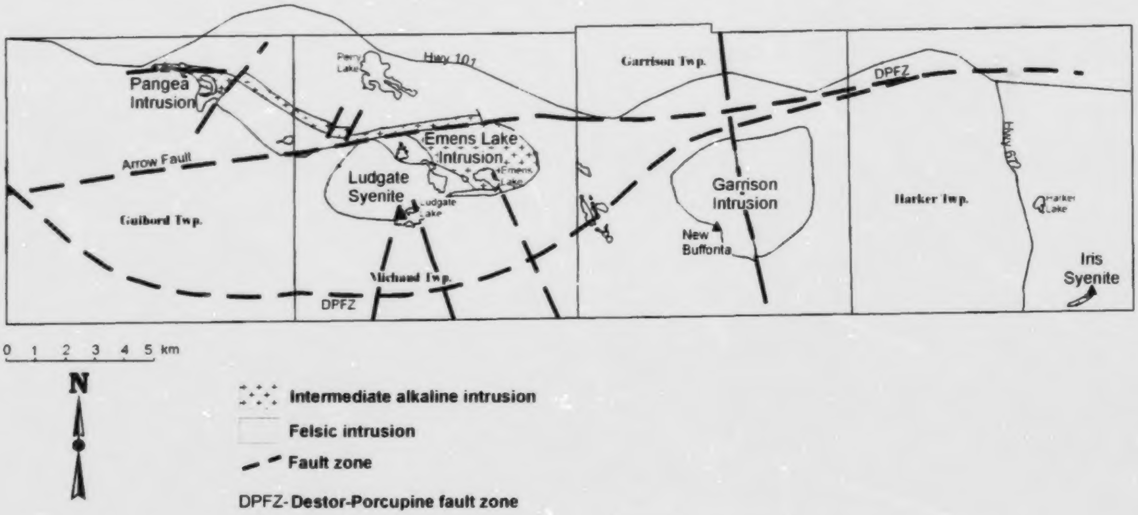

Figure 8.1. Location map of study area.

purpose of our discussion. Three groups were defined as follows: 1) the Emens and Pangea intrusions, 2) the Iris and Ludgate intrusions and 3) the Garrison intrusion. The most important compositional distinction between these groups is their alkaline nature. The Emens and Pangea intrusions both have high alkaline affinities, with the majority of their analyses plotting in the undersaturated field of the total alkali-silica diagram of Le Bas et al. (1986), whereas the Iris and Ludgate intrusions both have the majority of their analyses plotting in the SiO_2 saturated portion of the diagram. The analyses from the Garrison intrusion also plot in the SiO_2 saturated portion of the diagram but the geochemical properties of this intrusion differ considerably from the Iris and Ludgate intrusions (Figure 8.2).

The Emens and Pangea Intrusions

Rocks of the Emens and Pangea intrusions are principally feldspar-porphyritic hornblende and/or clinopyroxene melanosyenites. Both intrusions also contain a minor syenite component. These two intrusions are grouped together because of their common alkaline nature. This is especially true for the Emens intrusion for which all the samples analysed (n=21) yielded normative nepheline ($\bar{x}$ = 6.15 wt %), with some samples also displaying normative leucite. Similarly, the Pangea melanosyenite also yielded normative nepheline but not as commonly as the Emens melanosyenite. No analysis from the Emens intrusion showed normative quartz. The majority of the samples analysed are of intermediate composition with an average SiO_2 content of 51.20 wt.% ± 2.07 (n=42, α=0.05)[3]. Both intrusions show a wide range of K_2O/Na_2O values with an average of 1.54 ± 0.32 (n=42, α=0.05) (Figure 8.3). All analyses of the

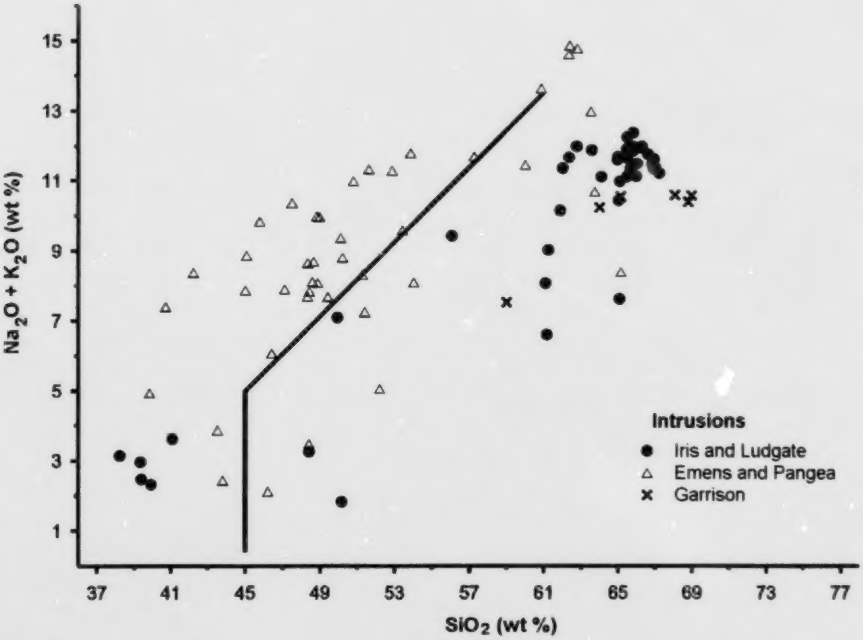

Figure 8.2. Total alkali silica-diagram (Le Bas et al. 1986) illustrating the more pronounced alkaline nature of the Emens and Pangea intrusions.

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[3] Confidence intervals on averages are calculated using: $\bar{x} \pm t_{\alpha\, 2,n-1}\, s/\sqrt{n}$

syenite from the Emens intrusion are potassium enriched (K_2O/Na_2O average value of 2.53) and nepheline normative, whereas those from Pangea are sodium enriched ($\bar{x} = 0.52$) and may also be nepheline normative.

The chondrite normalized rare earth element (REE) diagram for the Emens and Pangea melanosyenites shows a strong enrichment in the LREE (up to 600 times chondrite) and a more moderate enrichment in the HREE (10 to 50 times chondrite) (Figure 8.4). The patterns have a pronounced negative slope with an average La/Lu ratio of 31.70 ± 11.64 (n=8, α=0.05). Two samples of hornblendite from the Pangea intrusion have nearly flat patterns with a moderate enrichment in the LREE and HREE (20 to 60 times chondrite) and an average La/Lu ratio of 2.23.

The Iris and Ludgate Intrusions

The Iris and Ludgate intrusions are composed mainly of coarse-grained alkali-feldspar syenites, however, mafic and intermediate rocks are also present at Iris. The syenites from the two intrusions are quartz normative with an average quartz content of approximately 2 wt %. Nepheline is not present in the norm of the felsic rocks but some mafic rocks at Iris show minor amounts of normative nepheline. The SiO_2 content of these intrusions is quite variable, ranging from 40 wt % in the mafic rocks to 68 wt % in the syenites. The average SiO_2 content of all rocks from both intrusions is 60.47 wt % ± 2.87 (n=41, α=0.05). Numerous samples show an important and significant enrichment in sodium which is reflected in an average K_2O/Na_2O value of 0.30 ± 0.07 (n=41, α=0.05) (Figure 8.5). The syenites are especially sodic in nature with an average Na_2O content of 8.95 wt % ± 0.53 (n=33, α=0.05).

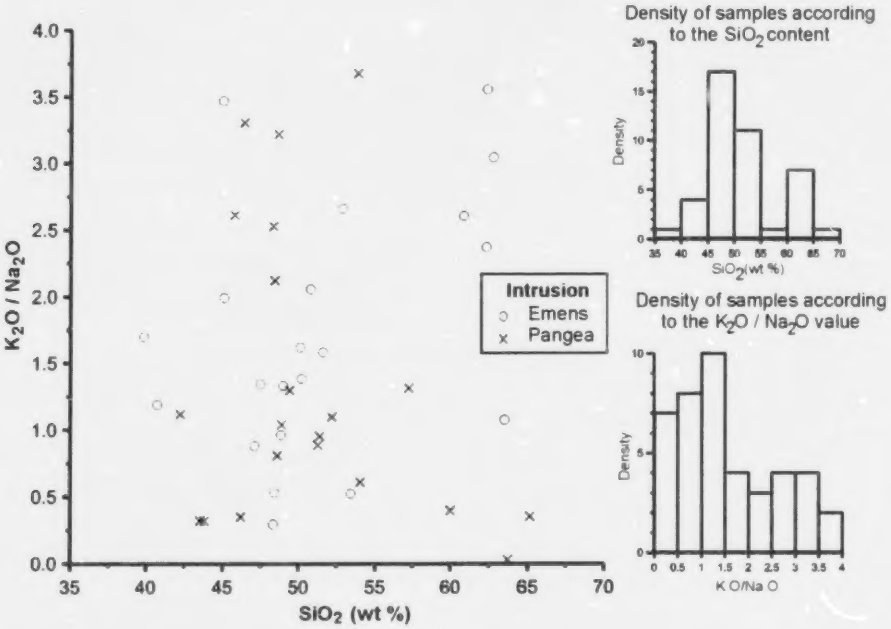

Figure 8.3. K_2O/Na_2O(wt % ratio) as a function of SiO_2 content in rocks from the Emens and Pangea intrusions.

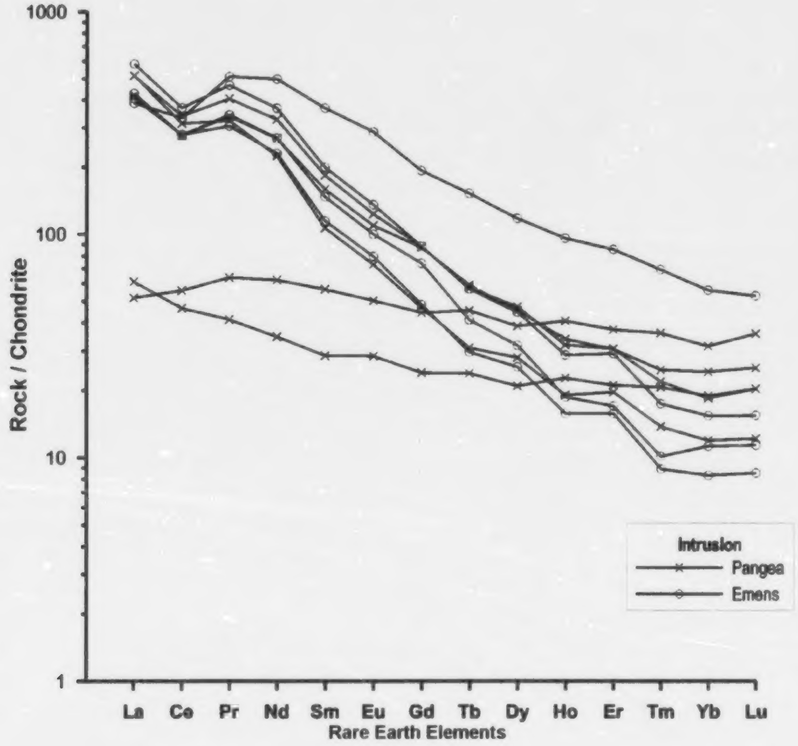

Figure 8.4. Chondrite normalized REE diagram for the Emens and Pangea intrusions. Chondrite values from McDonough and Sun (1995).

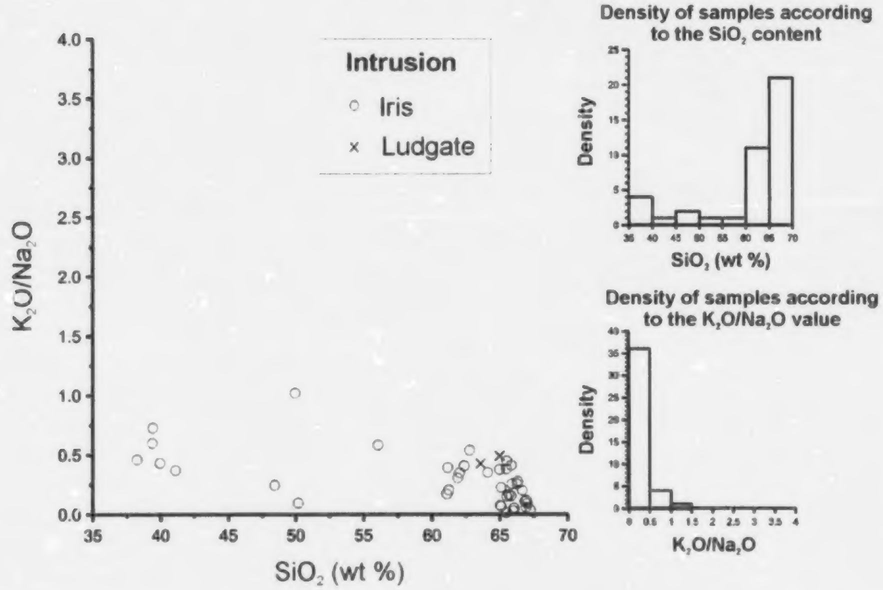

Figure 8.5. K_2O/Na_2O (wt % ratio) as a function of SiO_2 content in rocks from the Iris and Ludgate intrusions.

The chondrite normalized REE diagram of the Iris and Ludgate intrusions are presented in Figure 8.6. The mafic rocks of Iris are more enriched in REE than the felsic ones. They show a strong enrichment in the LREE (150 to 300 times chondrite) and a moderate enrichment in the HREE (20 to 35 times chondrite). The patterns have moderate negative slopes with an average La/Lu of 8.55± 2.20 ($n = 7$, $\alpha = 0.05$). The cause of the relative REE enrichment that is observed in the mafic rocks of the Iris intrusion is not well understood. The high modal abundance of accessory titanite in these mafic rocks, in contrast to the near absence of this mineral in the more felsic syenites, may be a likely cause. The syenites are moderately enriched in LREE (30 to 100 times chondrite) and slightly enriched in the HREE (3 to 15 times chondrite). The REE patterns of the syenites have a peculiar curved shape, they show decreasing abundances from La to Tb and then slight increases from Tb to Lu. The average La/Lu ratio is 7.96 ± 1.30 ($n = 11$, $\alpha = 0.05$). The Ludgate syenites are enriched in LREE (90 to 110 times chondrite) and are slightly enriched in HREE (3.5 to 4 times chondrite). The patterns have strong negative slopes with an average La/Lu ratio of 27.33.

The Garrison Intrusion

The Garrison intrusion is composed of medium-grained hornblende-biotite monzonite to quartz monzonite. The samples from Garrison are all quartz normative ($\bar{x} = 11.31$ wt %) and nepheline is never present in the norm. The average SiO_2 content of all samples analysed is 65.67 wt % ± 4.04 (n=6, α=0.05).

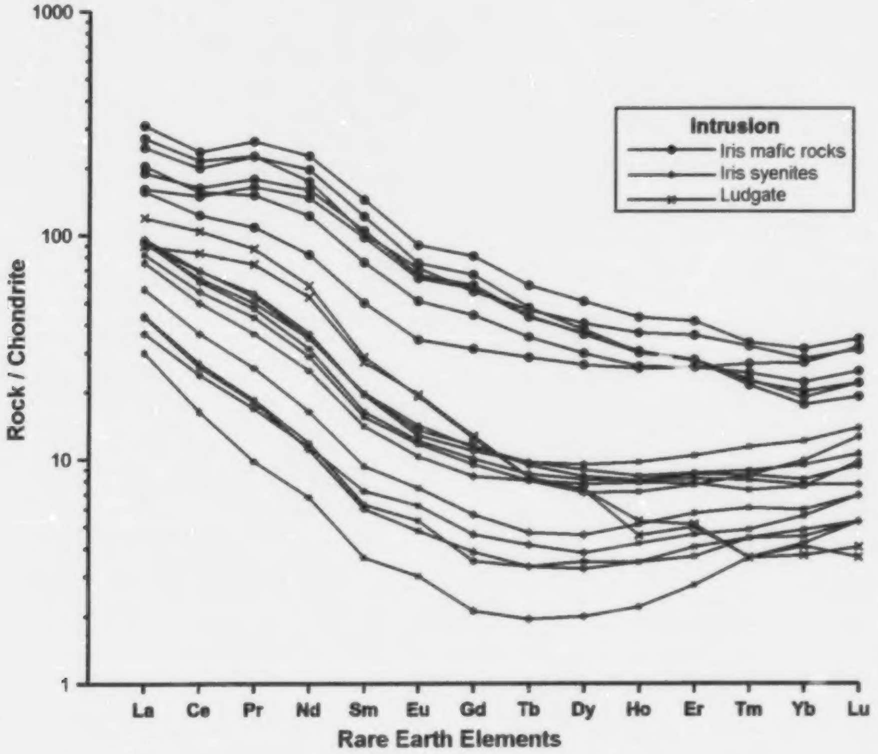

Figure 8.6. Chondrite normalized REE diagram for the Iris and Ludgate intrusions. Chondrite values from McDonough and Sun (1995).

The average K_2O/Na_2O value is 0.77 ± 0.18 (n=6, α=0.05). Samples from Garrison are enriched in the LREE (160 to 220 times chondrite) and slightly enriched in HREE (5 to 7 times chondrite). The patterns have a pronounced negative slope with an average La/Lu ratio of 32.46.

The suite of intrusions studied showed considerable variations in their geochemical compositions. The Emens and Pangea intrusions exhibited undersaturated characteristics, with the majority of their samples displaying normative nepheline. In contrast, the samples from the Iris and Ludgate intrusions have a more saturated nature, with most of them showing normative quartz. Furthermore, the Iris and Ludgate intrusions were highly enriched in sodium whereas the Emens and Pangea intrusions have a more potassic signature. The samples from the Garrison intrusion were all quartz normative and showed no significant enrichment in sodium.

The intrusions of the Destor–Porcupine fault zone share numerous geochemical and petrological properties in common with those of the Cadillac–Larder Lake fault zone in the Kirkland Lake region to the south. For example, the association of quartz-bearing and feldspathoid-bearing suites, identified here in the Iris–Ludgate and Emens–Pangea groups was also recognized in the Kirkland Lake region by Levesque et al. (1991). Given the close spatial association of these intrusions with the gold mineralization along both fault zones, our current efforts on the Destor–Porcupine intrusive rocks will focus on documenting the relative redox state under which the magmas evolved by means of mineral-chemical studies in order to better evaluate the potential contribution these magmas may have made to the mineralization process.

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9. Project Unit 00-042. Structural Study of the Kenogamissi Batholith and Surrounding Swayze/Abitibi Greenstone Belt

J.K. Becker[1] **and K. Benn**[1]

[1]Ottawa–Carleton Geoscience Centre and University of Ottawa, Department of Earth Sciences

INTRODUCTION

Numerous greenstone belts have been discovered and investigated worldwide with the Abitibi–Swayze greenstone belt probably being one of the most intensely studied examples. Highly sophisticated techniques have been used to investigate the greenstone belts, for example, geophysical and seismic data show that most greenstone belts are less than 10 km thick and commonly display steeply dipping structures that bend into horizontally layered structures at depth (Stettler et al. 1997). There is now a general agreement that many greenstone belts formed as a result of seafloor-spreading, followed by subduction, magmatic arc development and accretionary processes (e.g., resulting from horizontal extension or shortening; Windley 1995). One remaining question is the role of the ubiquitous, large granitoid intrusions in these greenstone belts. Since these intrusions usually only contain minor, if any, mineral deposits they are not as well characterized, therefore little is known about the mechanisms of granitoid intrusions in Archean cratons (see compilation of data in Ridley et al. 1997). Generally, five different mechanisms of emplacement have been recognized (diapirism, ballooning, stoping, regional deformation and diking), each of which may lead to differing economic mineral content in the surrounding host rocks or in the granitoid body itself. Furthermore, the mineral content depends on the origin of the ascending magma (I- or S-type). The granitoid batholiths are usually studied to recognize the emplacement history of the plutons themselves (e.g., Ramsay 1989; Kisters and Anhaeusser 1995; Schiotte and Campbell 1996). More rarely is the connection of the emplacement history of batholiths with the evolution of the bordering greenstones and mineralizations the subject of a thorough study. This is surprising since from the emplacement mechanism of the batholiths and the information obtained from study of the adjacent greenstones a wealth of information can be obtained. This information can be used to develop a model for the evolution and crustal formation of the craton, including possible mineral deposits in the host rocks of the batholith. The chosen working area of the Kenogamissi batholith is structurally comparable to other granitoid intrusions in greenstones (e.g., Chinamora batholith, Zimbabwe, *see* Becker et al., in press) and can therefore provide information on crustal and mineral deposit development during the last stages of the formation of continental crust. The project is funded by the German Research foundation, the University of Ottawa and the Ontario Geological Survey.

REGIONAL GEOLOGY

Swayze–Abitibi Greenstone Belt

Metavolcanic rocks and associated metasedimentary units make up the southern Abitibi greenstone belt. Synvolcanic intrusions of peridotitic to granodioritc affinity are also widespread within the Abitibi greenstone belt. The Kenogamissi batholith separates the Swayze greenstone belt from the Abitibi greenstone belt. The Abitibi greenstone belt is one of the most intensely studied greenstone belts in Canada, possibly worldwide, and displays a complex succession of volcanic, sedimentary and granitic rocks which typically have undergone greenschist- to subgreenschist-facies metamorphism (Jolly 1978). Locally, amphibolitic metamorphic facies can be observed within the contact metamorphic aureoles of large granitic intrusions. The Abitibi greenstone belt is one of the most prolific mineral-producing greenstone belts (both precious and base metals), and the Swayze greenstone belt is also becoming an important target area for mineral exploration. The Swayze greenstone belt is now seen as the southwestern extension of the Abitibi greenstone belt (Heather 1998) and is connected with the Abitibi greenstone belt by volcano-sedimentary units that wrap around the northern and southern margins of the Kenogamissi batholith.

The Swayze greenstone belt displays a tectonic history that includes polyphase folding, several generations of fabrics, high-strain zones and late brittle deformation. The first deformational event (D_1) is not well constrained and appears to be minimal in the Swayze greenstone belt due to a strain shadow effect (Heather et al. 1995). It displays penetrative foliation (S_1) and isoclinal, commonly intrafolial folds (F_1). The Swayze greenstone belt is dominated by regional, east-trending antiforms and synforms (F_2) with an associated axial planar foliation (S_2). The penetrative S_1 foliation is folded about F_2 folds. Later deformational events (D_3 to D_7) affected the whole Abitibi greenstone belt and led to the formation of high strain zones (shear zones, usually showing a sinistral sense of shear) and brittle faults throughout the area. However, age relationships of these later deformations are not well constrained. According to Heather (1998), these structures should not necessarily be assigned to different deformational events. In fact, it is assumed that during progressive deformation more than one deformational pattern indicating conflicting types of origin may have developed, possibly due to the interference between, on one hand, the stresses related to batholith emplacement, and on the other, regional tectonic stresses. Bedding and tectonic fabric generally dip steeply to moderately, however shallow dips are present in the Swayze area as well (Jackson and Fyon 1991), probably within the hinge zones of regional-scale folds.

Kenogamissi Batholith

The Kenogamissi batholith is a large granitoid complex separating the Swayze greenstone belt from the Abitibi greenstone belt in the east. It consists of a complex sequence of crosscutting intrusive phases which, from oldest to youngest, are: a) synvolcanic diorite, biotite and hornblende tonalite (trondhjemite) and granodiorite intrusions, b) syntectonic hornblende granodiorite intrusions, c) a transitional group between (a) and (b) that includes tonalite to quartz monzonite intrusions, d) a second transitional suite between (b) and (e) including dioritic to monzonitic intrusions and e) posttectonic granite intrusions (Heather 1998). The synvolcanic intrusions (a) are typically sheet-like (laccoliths?); they vary from massive and non-foliated to gneissic in texture and are sometimes in direct contact with the greenstones (Heather 1998). According to Heather (1998) the greenstones show both flattening and stretching fabrics parallel to the granitoid contact. The syntectonic intrusions (c) are sheet-like as well, and are localized along the contact area of synvolcanic intrusions (b) and greenstone belt rocks (Heather 1998). In addition, they also occur as discrete plutons and stocks within both the greenstone belt and the synvolcanic intrusions. The posttectonic granite intrusions (e) are described by Heather (1998) to occur as large batholiths and dyke swarms within the synvolcanic and syntectonic intrusions but do not occur in the greenstone belt and only rarely adjacent to it. In earlier publications (Heather et al. 1994, 1995, 1996) most of these units have been described as distinct diapirs. A schematic time/space diagram summarizing the plutonic ascent and deformation histories shows these intrusions as distinct diapirs as well with the time span of intrusion of the different lithologies in the range between 2700–2660 Ma (Heather 1998).

PROJECT AIMS

Three major aims are included in this project:

1. To understand the emplacement mechanism of the Kenogamissi batholith and the postemplacement deformation (if any) that led to the observed fabric. For this purpose an intense study of the fabric of the different units of the Kenogamissi batholith will be performed. From the internal fabric the overall form of the batholith and its deformational history can be estimated which will yield information on the emplacement mechanism.
2. To reveal the deformation in the greenstones that resulted from the emplacement of the granitoid magmas as well as pre- or postemplacement fabrics with special reference to the epigenetic gold deposits related to deformation zones in the surrounding greenstone belt.
3. To determine the role of the ascent, emplacement and deformation of the granitoids and greenstones in crustal formation. Is the formation of continental crust comparable in different cratons? Are mineral deposits in the greenstone belts related to the emplacement and/or induced metamorphic overprint of the granitoid rocks, or are they related to shear zones?

METHODOLOGY

Samples taken from the batholith will be used to perform AMS (Anisotropy of Magnetic Susceptibility) measurements using a Kappabridge a.c. susceptibility bridge. The samples are put into a magnetic field of 0.5 mT. The paramagnetic (e.g., biotite and hornblende) and ferrimagnetic (sensu lato, e.g., magnetite and haematite) minerals in the specimen induce a magnetic field which is measured in 15 different orientations. These measurements can be used to calculate a second rank tensor that describes the magnetic properties of the sample in any given direction. From the second rank tensor, the magnetic foliation and magnetic lineation can be calculated. If no ore minerals are present in the sample, the measured magnetic fabric is parallel to the macro- or microscopic fabric.

1. Since most of the outcrops were expected to have a smooth surface with few edges to take hand specimen a drill was used to obtain the necessary cores for the magnetic measurements. The drill, a refitted chainsaw, can drill cores of 25 mm in diameter with a maximum length of approx. 15 cm. Depending on the hardness of the granitoid (which varies greatly with mineral content) one core takes about 5 to 10 minutes to drill.
2. Measurements of the fabric (foliation and, where possible, lineation) were performed in each outcrop regardless whether cores were taken or not. Additionally, the orientations of shear zones, dip and plunge of folds or orientation of the crenulation cleavage was measured in the greenstone.
3. Since the southern lobe of the Kenogamissi batholith (the focus of this years field work) is divided into 3 main units which have not been dated yet, hand specimens of each unit were taken for dating. The zircon ages will help in determining the emplacement history and furthermore the timing of the emplacement of the different units.

SUMMARY

During this year's field-season a total of 204 outcrops were studied. Hand specimen or cores were collected from approximately 100 of these, which will provide 300–350 cores (3–6 cores were drilled per outcrop). The cores will be used for magnetic fabric measurements; hand specimens and the remains of the cores will be used to obtain oriented thin sections for structural and petrographic observations.

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10. Project Unit 99-020. Temporal and Spatial Variations in Komatiite Geochemistry in the Abitibi Greenstone Belt

R.A. Sproule[1], C.M. Lesher[1], J.A. Ayer[2] and P.C. Thurston[2]

[1]Mineral Exploration Research Centre, Laurentian University
[2] Precambrian Geoscience Section, Ontario Geological Survey

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INTRODUCTION

Komatiite are ultramafic volcanic rocks that occur mainly in Archean greenstone belts. As the products of high degree partial melting of the mantle, they provide important constraints on the composition and structure of the Archean mantle, the relationship between plumes and tectonic processes, and the stratigraphy and structure of Archean greenstone belts. Komatiite may also host Ni-Cu-PGE sulphide ores, so an understanding of their genesis can aid in exploration for deposits of this type.

The ~2.7 Ga Abitibi greenstone belt contains several lithologically-distinct and probably structurally-repeated volcano-sedimentary assemblages that may be subdivided into several stratigraphically- and structurally-distinct terranes. The relationships between terranes is ambiguous and the greenstone belt may represent 1) a collage of allochthonous terranes, each representing a single lithotectonic assemblage formed in a different tectonic setting (e.g., Jackson and Fyon 1991; Jackson et al. 1994); 2) a single autochthonous terrane representing a series of assemblages formed along a stratigraphically and tectonically-complex and structurally-deformed convergent margin (e.g., Heather 1998, Ayer et al. 1999, 2000), or 3) a combination of the two models.

Based on an extensive database of U-Pb zircon dating, Ayer et al. (1999, 2000) have modified previous interpretations of the tectono-stratigraphy of the Abitibi greenstone belt and have subdivided it into 9 assemblages, summarized in Figure 10.1. Ultramafic and mafic volcanic rocks, including komatiite,

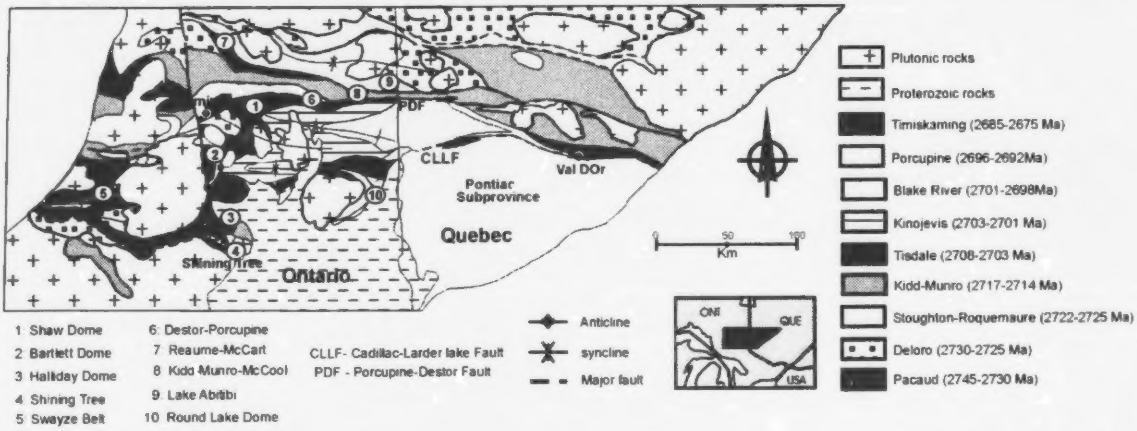

Figure 10.1. Assemblage map of the Abitibi greenstone belt (after Ayer et al. 1999).

komatiitic basalts, picrites, and tholeiites outcrop throughout the Abitibi greenstone belt, predominantly in the Southern Volcanic Zone. Komatiite (sensu stricto) occur in only 4 of the assemblages in the Abitibi greenstone belt, but they all occur within the 2750–2700 age interval and occur at similar stratigraphic levels. As such, the stratigraphy of komatiite in the Abitibi greenstone belt appears to be broadly similar over the entire Abitibi greenstone belt within the interval ~2745 to ~2703 Ma. Thus, komatiite geochemistry and geochronology may provide critical information on the continuity of assemblages, which in turn has ramifications for development of tectonic models.

AIMS

The general aims of this study are to:

1. Define komatiite geochemical groupings within the Abitibi greenstone belt, using a combination of existing databases and new data, determine how these groupings correspond to terrane boundaries, and, if systematic variations exist, attempt to understand the processes that control the variations.
2. Examine the variations in komatiite geochemistry within the stratigraphic framework defined by Ayer et al. (1998) to determine whether this framework is valid and whether komatiite geochemical trends vary systematically with stratigraphic position.
3. Characterize the mantle source region(s) for the komatiite and examine the relative importance of igneous processes such as partial melting, fractional crystallization, and lithospheric contamination, and subsequent processes such as metamorphism and alteration in developing the geochemical characteristics.
4. Consider the implications of komatiite geochemical variation on the tectonic development of the Abitibi greenstone belt (i.e., allochthonous vs. autochthonous models) and examine the nature of the underlying basement (i.e., evidence of lithospheric interaction).
5. Establish the sulphide saturation state of the komatiite, with implications for mineralization potential of the Abitibi greenstone belt komatiite, to determine whether certain portions of the komatiitic stratigraphy are more prospective for komatiite-hosted Ni-Cu-(PGE) mineralization.

METHODOLOGY

Our database presently includes 2185 komatiite and komatiitic basalt from both Ontario and Quebec derived from data provided by Outokumpu Mines Ltd. (Stone and Lesher 1995), the Ontario Geological Survey (OGS), and the Geological Survey of Canada (GSC), and data extracted from the literature (e.g., Arndt and Nesbitt 1982; Arndt 1986, 1989; Barnes et al. 1981; Cattell and Arndt 1987; Coad 1976; Dostal and Mueller 1997; Eakins 1972; Fan and Kerrich 1997; Fleet and McRae 1972; Gelinas et al. 1977; Ludden and Gelinas 1982; Nesbitt, and Sun 1976; Xie et al. 1993).

ALTERATION

As discussed by Sproule et al. (1999, 2000), all komatiite in the Abitibi greenstone belt have experienced some degree of hydrothermal alteration, seafloor alteration, and/or regional metamorphism (e.g., Arndt 1986, 1994; Arndt et al. 1989; Lahaye and Arndt 1996; Lesher et al. 1997). Such processes are capable of mobilizing elements and resetting isotopic compositions. Numerous studies on komatiite have shown this to be the case for selected elements under selected conditions in komatiite (e.g., Lahaye and Arndt 1996; Arndt et al. 1989; Tourpin et al. 1991). However, many magmatic geochemical characteristics of komatiite are still retained. In particular, elements with small ionic radii and high charges (e.g., REE, Y, Zr, Nb, Hf, Ta and Th) that are housed in alteration-resistant accessory phases are often relatively immobile (*see* e.g., Arndt 1986; Lesher and Stone 1996). However, Lahaye and Arndt (1996) reported significant mobility of these elements during carbonatisation. Elements that are housed in relict igneous phases or in metamorphic minerals such as amphibole and chlorite, including Ti, Cr, V, Mn, Fe, Mg, Ni, and Co are also relatively immobile. In contrast, monovalent large-ion lithophile elements (e.g., Cs, Rb, K, Na) and divalent calc-alkaline elements (e.g., Sr, Ba, Ca, and also Eu) are not accommodated in the secondary serpentine, chlorite, or magnetite and are easily complexed in metamorphic fluids, so they are typically mobile (Lesher and Stone 1996). Si may be mobile during high degrees of serpentinization, rodingitization (rocks which have experienced Ca-addition and desilicification and consist of various proportions of Ca-Al silicates including epidote, Ca-rich garnets, diopside, tremolite and chlorite), steatization (talc-carbonate alteration), and chloritization (O'Hanley 1995; Lahaye and Arndt 1996; Lesher and Stone 1996).

In order to remove the affects of alteration from our dataset, we compared the trends of major and trace element abundances on MgO variation diagrams and on Pearce cation plots with those expected from normal igneous processes (olivine-chromite fractionation). Our results are similar to those obtained by previous workers and indicate that Ti, V, Mn, Fe, Mg, Ni, Co, Cr, and Zr appear to have been generally immobile and that Cs, Rb, K, Na, Sr, Ba, Ca, and Eu have been mobile. Si and Al exhibit some degree of dispersion, typically associated with pervasive chloritization. In order to exclude samples exhibiting other than normal hydration associated with serpentinization, the following filters were applied:

- good textural preservation (indicating minimal volume changes) and lack of veining
- low H_2O and CO_2 contents ($0.15\ MgO(raw) - LOI + 8 > 0$)
- "normal" chlorite, amphibole, and serpentine contents ($\{Al_2O_3 - 1.67 * SiO_2 + 66.7 < 0\}$ and $\{Al_2O_3 - 0.3 * SiO_2 + 13 < 0\}$); the second filter for amphibole is only applied when MgO (anhydrous) > 23 wt.% (i.e., this filter normally applies only to cumulate komatiite)

After filtering, the database included 1820 komatiite analyses.

KOMATIITE PETROGENESIS IN THE ABITIBI GREENSTONE BELT

In order to simplify the discussion, we have subdivided the komatiitic rocks into 4 groups on the basis of their anhydrous MgO content: *komatiitic basalt* (12–18 wt.% MgO), *komatiite* (18–27 wt.%), *komatiitic peridotite* (27-42 wt% MgO), and *komatiitic dunite* (>42% MgO). Major element trends are strongly controlled by olivine fractionation and accumulation in dunite, peridotite, and komatiite, and by olivine ± chromite fractionation and accumulation in komatiitic basalt.

Komatiite in the Abitibi greenstone belt can be divided into 3 types on the basis of Al-contents and Al/Ti ratios: Al-depleted komatiite (ADK), Al-undepleted komatiite (AUK), and Al-enriched komatiite (AEK). Table 10.1 summarizes the geochemical features of each of the komatiite types, and their interpreted source region and petrogenesis. Mantle-derived plumes are favored as the source region of komatiite as they represent hotter parts of the mantle appropriate for developing the extremely high degrees of partial melting required to form komatiite (up to 60%: Campbell et al. 1989; Lesher and Stone 1996). Different komatiite types are hypothesized to be derived by variable degrees of partial melting in different parts of the plume at different depths (Herzberg and Ohtani 1988; Herzberg and O'Hara 1998). Figure 10.2 shows a histogram of Al_2O_3/TiO_2 ratios for all komatiite throughout the Abitibi greenstone belt. We recognize that there is some bias in the database for the more voluminous younger komatiite in the Abitibi greenstone belt (Tisdale and Kidd Munro Assemblage), however, there are clearly two

Table 10.1. Summary of the geochemical characteristics of ADK, AUK and AEK and interpreted source regions (adapted in part from Herzberg and O'Hara 1998).

	Al-undepleted	**Al-depleted**	**Al-enriched**
Komatiite type	Munro Type	Barberton Type	Shining Tree Type
Al_2O_3/TiO_2	15-25	<15	25-35, and Al_2O_3>10%
Gd/Yb_{CN}	~1.0	1.2 - 4	0.6 – 0.8
Source type	*garnet lherzolite* [L+Ol+Opx+Cpx+Gar+sul.] or *garnet harzburgite* [L+Ol+Opx+Gar+sul]	*garnet lherzolite*[L+Ol+Opx+Cpx+Gar+sul.] or *garnet harzburgite* [L+Ol+Opx+Gar+sul]	*garnet-rich lherzolite* [L+Ol+Opx+Cpx+Gar+sul.] or *garnet-rich harzburgite* [L+Ol+Opx+Gar+sul]
Degree of partial melting	30-50%	20-40%	30-50%
Source residuum	*harzburgitic* [L+Ol+Opx] or *dunitic* [L+Ol] residuum	*garnet lherzolite* [L+Ol+Opx+Cpx+Gar] or *garnet harzburgite* [L+Ol+Opx+Gar] residuum	*harzburgitic* [L+Ol+Opx] or *dunitic* [L+Ol] residuum
Source region	Plume head at 2-8 GPa	Plume tail at 8-9 GPa	Plume head at 2-8 GPa

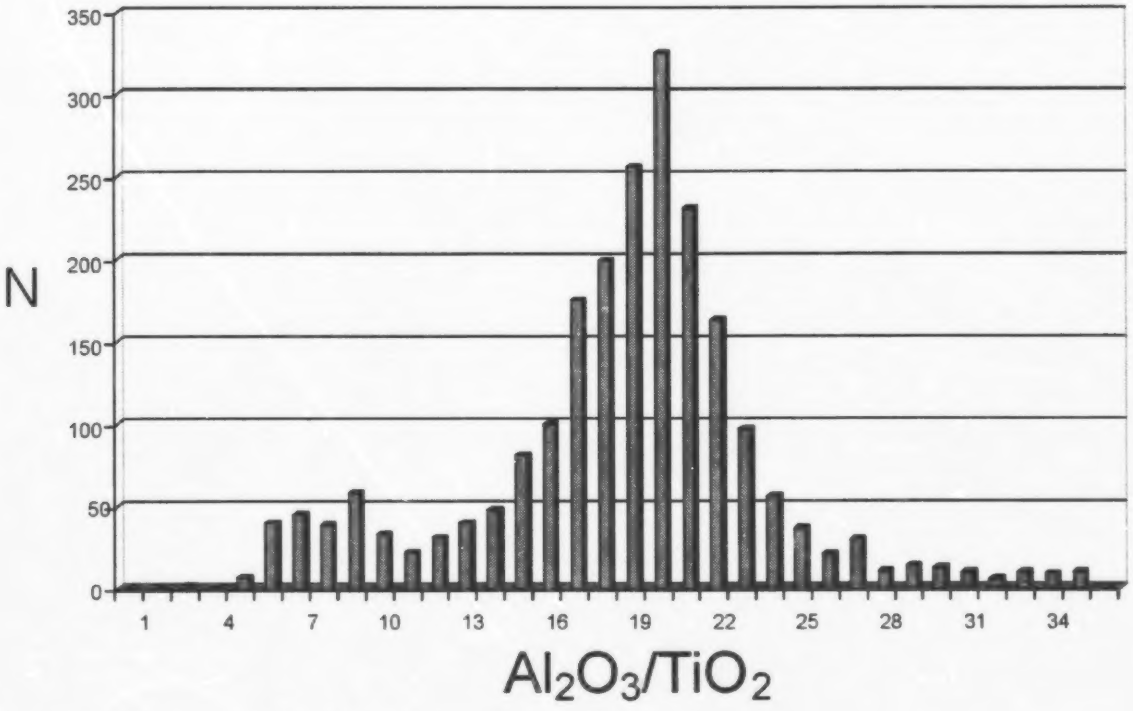

Figure 10.2. Histogram of Al_2O_3/TiO_2 values for komatiite in the Abitibi greenstone belt.

populations. One population has a mode at $Al_2O_3/TiO_2 \sim 10$ (corresponding to ADK or Barberton-type komatiite), the other has a mode at $Al_2O_3/TiO_2 \sim 22$ (corresponding to AUK or Munro-type komatiite). AEK are volumetrically minor, but their temporal importance will be discussed later. The occurrence of at least two populations in the komatiite, as opposed to a single population suggests derivation from two distinct plumes or two geochemically distinct sources within a single plume.

A majority of the komatiite are LREE depleted ($La/Sm_{CN} < 1$, where CN denotes chondrite normalized, using the normalisation scheme of McDonough and Sun 1995). However, those komatiite that are LREE enriched ($La/Sm_{CN} > 1$) have concomittant $Th/Nb_{MN} > 1$ (where MN denotes primitive mantle normalized, using the normalization scheme of McDonough and Sun 1995), implying the involvement of assimilation-fractional crystallization (AFC) processes (Figure 10.3). There is a significant range of La/Sm and Th/Nb ratios for all Abitibi greenstone belt komatiite, thus a single AFC model (DePaolo 1986) cannot account for all La/Sm and Th/Nb ranges (Figure 10.3). This is, of course, due to the effects of other processes including variations in source composition, variations in the degree (and type) of partial melting, variations in the composition of the contaminant(s), and variations in the A:FC ratio. However, AFC modelling using the equations of DePaolo (1986) and an average pelitic sediment as a contaminant suggest that most of the geochemical variations can be accommodated by varying the A:FC ratio at low degrees of FC, consistent with the primitive nature of the komatiite.

SPATIAL VARIATIONS

Figure 10.1 summarizes the spatial distributions of ADK, AUK, and AEK in the Abitibi greenstone belt.

- *Al-depleted komatiite* occur in all subregions of the Abitibi greenstone belt except the Bartlett and Halliday Domes. However, ADK with high Gd/Yb ratios ($Gd/Yb_{CN} > 1.2_{CN}$) are less common and are restricted to the Round Lake Dome, the Lake Abitibi region, and the Swayze greenstone belt.
- *Al-undepleted komatiite* are by far the most common type, occurring in all the regions of the Abitibi greenstone belt.
- *Al-enriched komatiite* are extremely uncommon. They may be further subdivided into two types. The first are LREE and HREE depleted ($La/Sm_{MN} < 0.70$ and $Gd/Yb_{MN} < 0.8$) and have thus far only been found in Shining Tree greenstone belt. The second are LREE and HREE undepleted and occur in the Swayze greenstone belt, the Lake Abitibi region, and the Shaw Dome.

If we assume that ADK are derived from a deep source (e.g., plume axis: *see* Figure 10.6) and that AUK and AEK are derived from a shallower source (e.g., inner plume head), plume-axis associated melts appear to occur both at the base of and in the central parts of the Abitibi greenstone belt volcanic sequence. Significant volumes of plume-axis associated magmas (ADK) occur over a wide geographic range (e.g., the Round Lake Dome, Lake Abitibi, and in the Swayze Belt). This indicates that deep-sourced komatiite occur over a very large part of the Abitibi greenstone belt (>300 km). No eruptive sites have been identified. Although komatiite magmas appear to have had very low viscosities (1–10 $g{\bullet}cm^{-1}{\bullet}sec^{-1}$), high densities (2.7–2.8 $g{\bullet}cm^{-3}$), high liquidus temperatures (1500-1600°C), a large interval between the liquidus and solidus (350–450°C), and high heat contents (ca 200 $cal{\bullet}g^{-1}$), and were probably capable of flowing long distances (Lesher et al. 1984; Huppert and Sparks 1985; Williams et al. 1998), it seem likely that they erupted from multiple vents. Indeed, the extent of komatiitic volcanism in the Abitibi greenstone belt is comparable to that observed for other higher viscosity plume-derived volcanic magmas (e.g., Siberian Trapps, Deccan Trapps, Columbia River Basalts). The large scale faults in the Abitibi greenstone belt (e.g., the Porcupine–Destor Fault and the Cadillac–Larder Lake Fault) hamper regional volcanological reconstructions and we cannot rule out the involvement of multiple plumes, but the extent of plume axis-related magmatism in the Abitibi greenstone belt is at a similar scale to that observed in many Proterozoic and Phanerozoic plume-related magmas, thus, it is possible that all of the observed magmatism may potentially be related to a single large plume.

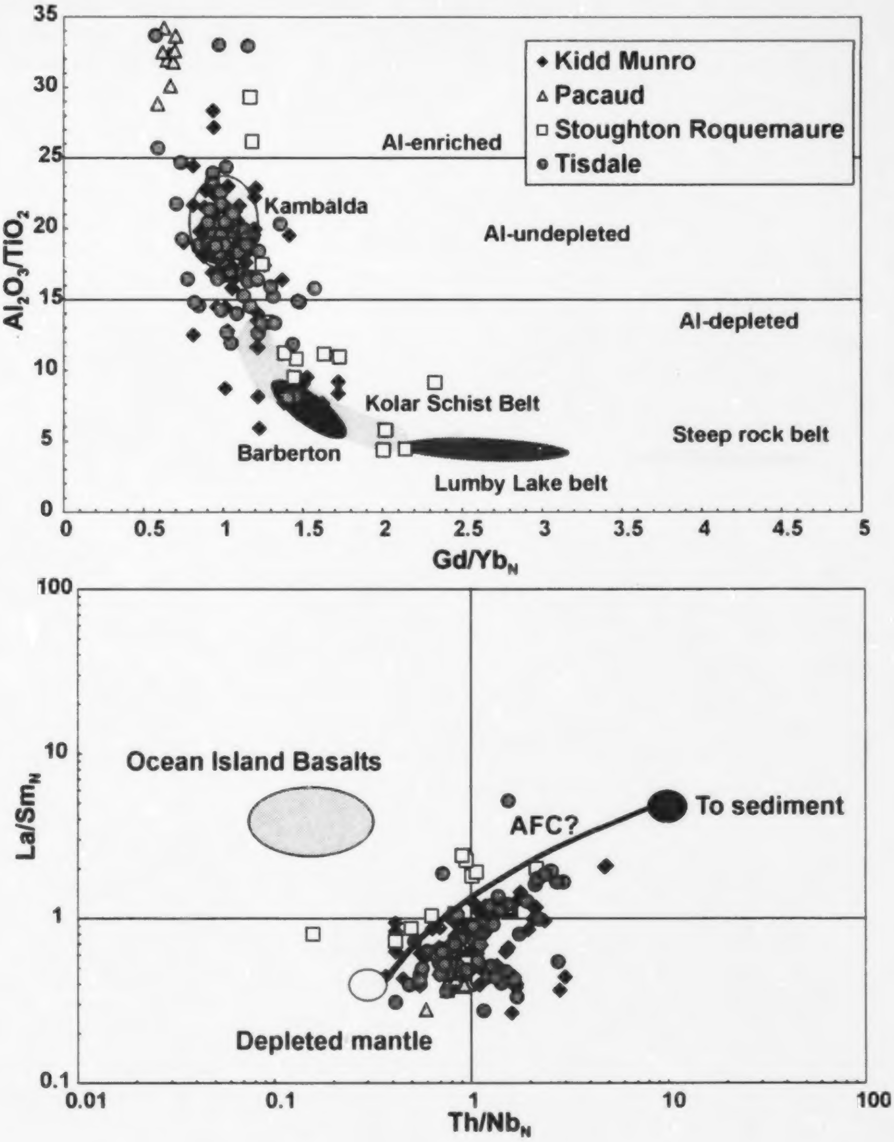

Figure 10.3. a) Al_2O_3/TiO_2 versus chondrite normalized Gd/Yb_N for komatiite from the Abitibi greenstone belt, with komatiite from Kambalda (Lesher, unpublished data), Kola Schist Belt, Barberton, Steep Rock and Lumby Lake (Western Superior Province; Tomlinson et al. 1998, 1999) for comparison. **b)** Primitive mantle normalized La/Sm_N versus Th/Nb_N for the Abitibi greenstone belt komatiite. An ocean island field is from Sun (1980) and Saunders and Tarney (1984). Sediment is an average Archean upper crust from Taylor and McLennan (1995). Normalising values from McDonough and Sun (1995).

TEMPORAL VARIATIONS

Komatiite are present within four assemblages in the Abitibi greenstone belt: 1) Pacaud assemblage (2.745–2.730 Ga), 2) Stoughton–Roquemaure assemblage (2.722–2.720 Ga), 3) Kidd Munro assemblage (2.717–2.712 Ga), and 4) Tisdale assemblage (2.708–2.703 Ga). Komatiite represent only a minor proportion of the lithologies present within each assemblage. There is <<1% by volume of komatiitic rocks in the Pacaud assemblage, ~2% in the Stoughton–Roquemaure assemblage, and ~5% in the Tisdale assemblage. Komatiite represent ~12% of the Kidd–Munro assemblage (T.C. Barrie, personal communication, 2000), thus the Kidd–Munro appears to contain the largest plume axis/inner plume head component of all Abitibi greenstone belt assemblages. Figure 10.4 shows the range of komatiite lithologies present within each of the stratigraphic units. The Pacaud Formation is composed of komatiitic basalts, komatiite, and komatiitic peridotite, but does not contain any komatiitic dunite (olivine meso-adcumulates). The Stoughton–Roquemaure assemblage is composed dominantly of komatiitic basalt, with lesser komatiite, komatiitic peridotite, and rare dunite. The Kidd–Munro and Tisdale assemblages contain lesser komatiitic basalts and komatiite and both contain much greater abundances of komatiitic peridotite and komatiitic dunite than the other assemblages. Thus far, komatiite-hosted Ni-Cu-(PGE) deposits have only been identified within the Kidd–Munro (e.g., Marbridge, Alexo, Dundonald) and Tisdale (e.g., Texmont, Redstone, Langmuir) assemblages of the Abitibi greenstone belt. This is consistent with the interpretation that komatiite-associated Ni-Cu-(PGE) deposits form within lava channel facies, not sheet flow or lava lobe facies (Lesher et al. 1984; Lesher 1989; Hill et al. 1995).

The geochemical signatures of the komatiite assemblages in the Abitibi greenstone belt are shown in Table 10.2. Only AEK with correspondingly low Gd/Yb_{CN} ratios occur in the Pacaud Assemblage. ADK are much more abundant in the Stoughton–Roquemaure assemblage than in the Kidd–Munro and Tisdale assemblages. The Kidd–Munro assemblage komatiite are composed dominantly of AUK with subordinate ADK. The Tisdale assemblage is composed almost entirely of AUK. Figure 10.5 shows a histogram of Al_2O_3/TiO_2 ratios for each of the assemblages. The Pacaud assemblage exhibits a highly skewed population with one weak mode. The Stoughton–Roquemaure comprises essentially one population, with a continuum from ADK to AUK, implying some mixing between source regions. This is supported by the ubiquitous $Gd/Yb_{CN} > 1$ even for AUK, implying some mixing of garnet-depleted signatures in the source region. The Kidd–Munro assemblage defines a bimodal Al_2O_3/TiO_2 population, with one minor peak at $Al_2O_3/TiO_2 = 10$ (ADK) and a major peak at $Al_2O_3/TiO_2 = 22$ (AUK). ADK and AUK in the Kidd–Munro assemblage overlap spatially. This suggests that these magma came from the same plume, and that they

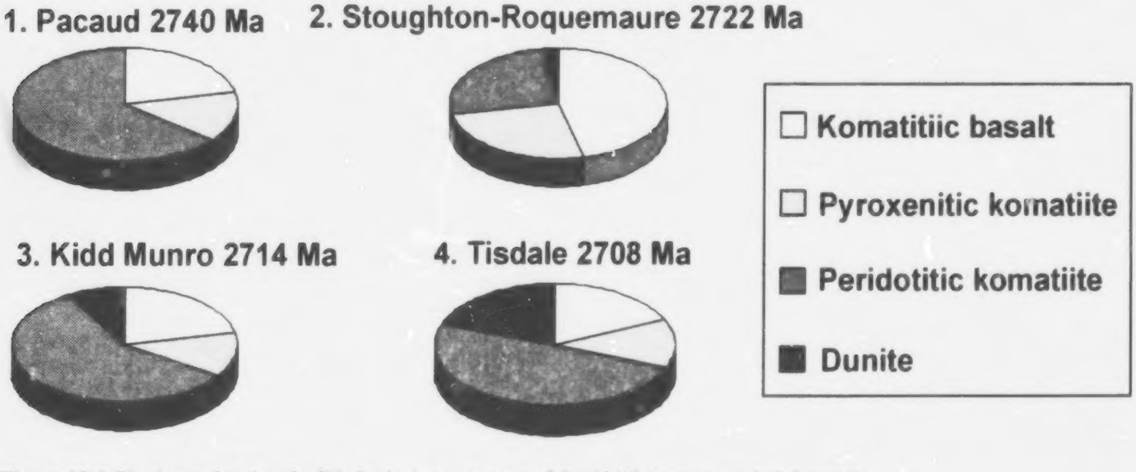

Figure 10.4. Pie charts showing the lithological components of the Abitibi greenstone belt komatiite.

Table 10.2. Summary of geochemical characteristics of stratigraphically assigned komatiite in the Abitibi greenstone belt.

	Pacaud	Stoughton-Roquemaure	Kidd-Munro	Tisdale
N	13	141	1108	444
Al_2O_3/TiO_2	AEK	AUK~ADK>AEK	AUK>ADK, minor AEK	AUK>>ADK, very minor AEK
Gd/Yb_{CN}	~0.6	>1	0.7-1.7, ave. 1.0	0.4-1.5, ave. 1.1
La/Sm_{CN}	<1	<1	>1<	>1<
Th/Nb_{MN}	<1	<1	>1<	>1<

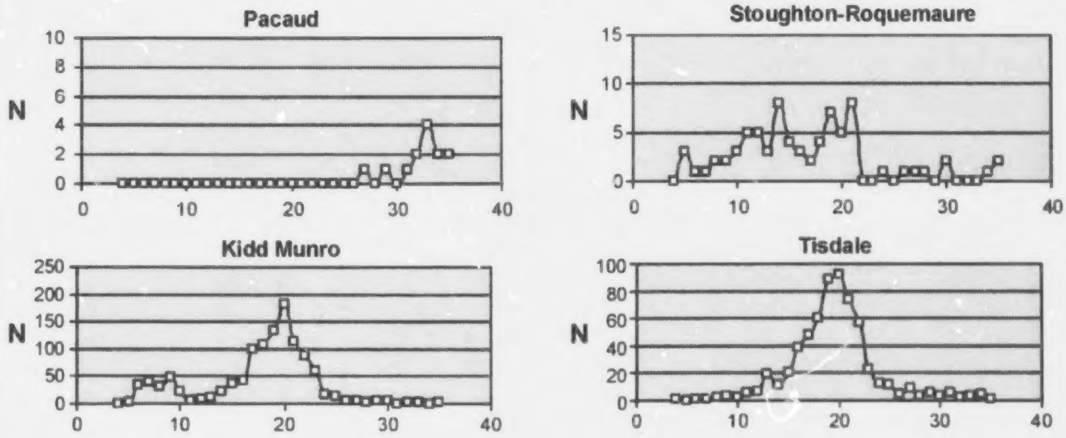

Figure 10.5. Histogram of Al_2O_3/TiO_2 values for komatiite from the Pacaud, Stoughton–Roquemaure, Kidd–Munro and Tisdale assemblages. N = number of samples.

potentially sampled different parts of the plume simultaneously. In contrast, the Tisdale assemblage comprises a single population, implying a single source and suggesting that the komatiite were derived from a more compositionally homogeneous part of the plume at similar depths.

The interpreted source region for each of the komatiite is shown on Figure 10.6. The Pacaud assemblage komatiite appear to be derived from an unusual garnet-enriched source (retention of garnet would explain the low Gd/Yb_{CN} ratios). These komatiite may potentially represent an earlier phase of plume-related magmatism.

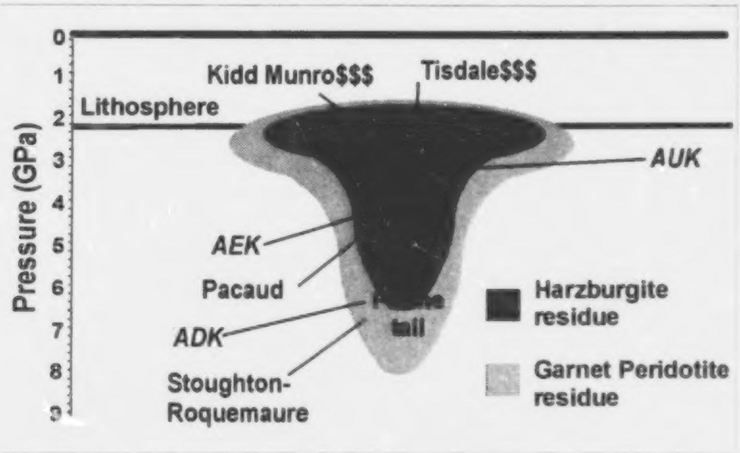

Figure 10.6. Model plume showing the hypothesized sources region of komatiite magma types in the Abitibi greenstone belt (from Herzberg and O'Hara 1998). Mineralized komatiite are shown with $$$.

The Stoughton–Roquemaure komatiite appear to be derived from a garnet-harzburgite or garnet-peridotite source where partial melting commenced at a higher pressure (greater depth) than for the Pacaud, Kidd–Munro and Tisdale komatiite. Garnet was retained in the residue, as indicated by the higher Gd/Yb_{CN} ratios. The unenriched La/Sm_{MN} and Th/Nb_{MN} signatures are similar to those obtained for typical depleted mantle melts, and unlike ocean island basalt sources that have low Th/Nb_{MN} but enriched La/Sm_{N}.

The Tisdale and Kidd–Munro komatiite are geochemically similar, however, the Tisdale contains less ADK, implying a shallower depth of partial melting compared to that of the Kidd–Munro. Both possess coupled low La/Sm_{MN} and Th/Nb_{MN} to high La/Sm_{MN} and Th/Nb_{MN}, suggesting contamination by crustal rocks.

The distinct secular variation in komatiite geochemistry in the Abitibi greenstone belt is consistent with a decreasing influence of garnet in the source region with time. This implies that there was either 1) a decrease in the amount of magma derived from the plume-axis relative to that derived from the plume head, potentially representing a change in plume morphology with time, for example as it flattened against the base of the lithosphere (Figure 10.7a), or 2) a rising plume ascending through the garnet stability field into the spinel stability field during the formation of the Abitibi greenstone belt (Figure 10.7b).

As previously mentioned, crustal contamination appears to have been an important part of the petrogenesis of some Kidd–Munro and Tisdale komatiite, but has not been observed in any of the other assemblages. This suggests a fundamental difference in the nature of the lithosphere through which the komatiite were erupted (or intruded) and/or a fundamental difference in discharge rates. For example, the Kidd–Munro and Tisdale assemblages may have erupted through an ensialic crust, whereas the Pacaud and Stoughton–Roqemaure may have erupted through an ensimatic crust. Regardless, the ensialic crust must have been juvenile, based on primitive Nd isotopic compositions (e.g., Dostal and Mueller 1997; Lesher et al. 1997).

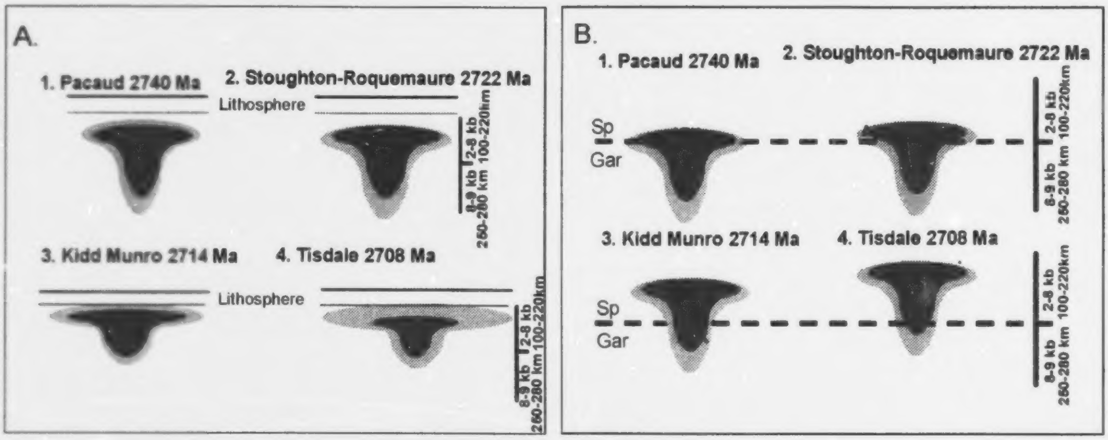

Figure 10.7. Models for the temporal change in komatiite geochemistry, reflecting **a)** a flattening of the plume against the lithosphere, and/or **b)** a rising plume. Sp, spinel; Gar, garnet.

ALLOCHTHONOUS OR AUTOCHTHONOUS DEVELOPMENT OF THE ABITIBI GREENSTONE BELT?

The komatiite in the Abitibi greenstone belt are distributed on a scale comparable to that observed for Phanerozoic plume-related magma and spatially disparate komatiite sequences of similar ages possess a similar geochemistry, suggesting derivation from similar sources and therefore possibly a single plume. The Abitibi greenstone belt has previously been subdivided into a series of allochthonous terranes, collated by plate-tectonic processes (e.g., Jackson and Fyon 1991). However, more recently Heather (1999) and Ayer et al. (1998, 1999) have proposed that the Abitibi greenstone belt formed via autochthonous processes in a structurally complex zone. However, we observe a distinct secular variation in komatiite geochemistry that transgresses formerly proposed allochthonous terrane boundaries, supporting an autochthonous model (Ayer et al. 1998, 1999, this volume). For example, the komatiite in the Stoughton–Roquemaure assemblage at the Round Lake Dome and in the Lake Abitibi area (which according to Jackson and Fyon (1991) represent separate terranes) are geochemically nearly identical but are quite distinctive compared to many Abitibi greenstone belt komatiite. Similarly, komatiite in the Tisdale Assemblage display a remarkably uniform geochemistry, which again traverses the Jackson and Fyon (1991) terrane boundaries.

IMPLICATIONS FOR EXPLORATION

Kambalda-type stratiform massive-disseminated Ni-Cu-(PGE) mineralization in the Abitibi greenstone belt is hosted only by the Tisdale assemblage (e.g., Hart, Langmuir, Redstone), the Kidd–Munro assemblage (e.g., Alexo, Dundonald), and the Dubuisson Formation (e.g., Marbridge) (Coad 1979; Imreh 1984; Davis 1999). These komatiite appear to have been generated from a garnet harzburgitic or garnet lherzolite source leaving a harzburgitic or dunitic residuum, similar to most (e.g., Kambalda, Zimbabwe), but not all (e.g., Forrestania, Ruth Well) mineralized komatiite world-wide (Lesher 1989; Lesher and Stone 1996). However, as the physical volcanology of the lavas is the most important factor in the development of komatiite-associated Ni-Cu-(PGE) deposits (Lesher et al. 1984; Lesher 1989), this may simply reflect greater degrees of lava channelization within those assemblages compared to other komatiite-bearing assemblages. In fact, olivine adcumulates, most likely representing replenished lava channels, occur only in the Kidd–Munro and Tisdale assemblages, reinforcing the importance of volcanic facies in the genesis of Kambalda-style Ni-Cu-(PGE) deposits. Also, only Kidd Munro and Tisdale komatiite show evidence of crustal interaction during their petrogenesis, which may also be a critical determinant in ore genesis, provided that this crustal interaction does not result in early S-saturation and consequent loss of Ni, Cu and PGE prior to eruption. A companion study (*see* Houlé et al., this volume) will focus on the physical volcanology of the komatiite.

Mount Keith-type strata-bound disseminated Ni-Cu-(PGE) mineralization in the Abitibi greenstone belt is hosted within thick lava flows and sills in the Tisdale assemblage (e.g., Bannockburn) and Kidd–Munro (?) assemblage (e.g., Dumont). Although the *presence* of disseminated sulphides can be used to infer potential for Kambalda-style Ni-Cu-(PGE) mineralization in the same stratigraphic unit (Barnes et al. 1999), the degree and distribution of sulphide saturation and contamination is strongly influenced by the stratigraphic architecture of the system (Lesher et al. 1999), so the *absence* of disseminated mineralization cannot be used to preclude mineralization elsewhere in the system.

FUTURE WORK

- Continue modelling petrogenetic processes to assess relative influences of partial melting, fractional crystallization, and contamination on the petrogenesis of the komatiite.
- Complete Sm-Nd and Re-Os isotopic work on key samples to explore changes in source region with time, and if possible the nature of the substrate with which the komatiite interacted.
- Examine the variation in chalcophile element abundances (PGE, Cu, Ni, and Co) within the komatiite and determine if and how they vary with other geochemical controls. These data will be used to constrain the nature of the mantle source region (e.g., fertile versus refractory harzburgitic), if and when the komatiite attained sulphide saturation, which factors controlled sulphide saturation, whether sulphide minerals were lost en route to the surface, and if so, when and where they were lost.
- Use this information to geochemically identify more favourable komatiitic sequences for Kambalda-style Ni-Cu-(PGE), Mt. Keith-style Ni-Cu-(PGE), and stratiform or stratabound PGE mineralization within the Abitibi greenstone belt.

SUMMARY

- Pacaud komatiite are enriched in Al and appear to be derived from a distinctive garnet-enriched source.
- Stoughton–Roquemaure komatiite are strongly depleted in Al, Sc, and HREE, suggesting garnet fractionation and/or retention of garnet in the source.
- Kidd–Munro and Tisdale komatiite contain both Al-depleted and Al-undepleted types. However, the Kidd–Munro assemblage contains a larger proportion of ADK compared to the Tisdale. This implies that more of the Kidd–Munro komatiite were generated in a garnet-bearing source compared to the Tisdale.
- AFC processes are observed in some Kidd–Munro and Tisdale komatiite.
- Overall, there appears to be a decreasing influence of garnet in and depth of the source region during the formation of the Abitibi greenstone belt, implying derivation from an ascending mantle plume or a change in plume morphology during plume evolution, potentially due to plume-lithosphere interaction.
- The uniformity of komatiite geochemistry crosses former terrane boundaries suggesting that the Abitibi greenstone belt formed either by autochthonous processes or by allochthonous processes if the terranes were originally located within the extent of the plume.

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11. Project Unit 99-021. Physical Volcanology and Metallogenesis of Komatiites in the Abitibi Greenstone Belt, Superior Province, Canada

M. Houlé[1,3], C.M. Lesher[1], A.D. Fowler[3], R.A. Sproule[1], J.A. Ayer[2], H.L. Gibson[1] and P.C. Thurston[2]

[1]Mineral Exploration Research Centre and Department of Earth Sciences, Laurentian University, Sudbury
[2]Precambrian Geoscience Section, Ontario Geological Survey
[3]Ottawa-Carleton Geoscience Centre and Department of Geology, Ottawa University, Ottawa

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INTRODUCTION

This project is part of a Ph.D. study based at Laurentian University and the University of Ottawa, under the supervision of Dr. Michael Lesher (Laurentian University) and Dr. Anthony Fowler (University of Ottawa). The aims of the study are to establish the volcanic facies of komatiites in the Abitibi Greenstone Belt (AGB) in order to constrain stratigraphic, tectonic and metallogenic models. The project will involve a minimum of two field seasons (2000 and 2001) in the Abitibi Subprovince in both Ontario and Québec. This study is complemented by a regional geochemical study of komatiites in the AGB (*see* Sproule et al., this volume).

GENERAL GEOLOGY

The Abitibi Greenstone Belt (AGB) is located in the Superior Province, the largest Archean craton in the world. The AGB may be divided in four zones: the Northern Volcanic Zone (NVZ), the Central Granite-Gneiss Zone, the Southern Volcanic Zone (SVZ), and the Southern Granite-Gneiss Zone (Ludden et al. 1986). Volcanic rocks crop out in the NVZ and SVZ. However, the rocks of interest to this study, komatiites, komatiitic basalts and picrites, occur predominantly in the SVZ.

Drawing analogies with plate tectonic models, Jackson and Fyon (1991) subdivided the AGB into more than 50 different assemblages, which they suggested represented accreted allochthonous *terranes*. However, recent work has defined a new stratigraphic framework of nine distinctive assemblages within the AGB in Ontario, interpreted to have developed authochthonously (Ayer et al. 1997, 1999a, 1992b).

In these new assemblages, seven are dominantly volcanic and two are dominantly sedimentary (*see* Table 11.1). Only four of the assemblages contain ultramafic rocks (Pacaud, Stoughton–Roquemaure, Kidd–Munro, and Tisdale assemblages).

As discussed above, many different tectonic models have been proposed for the development of the AGB. However, the formation of the AGB can be summarized into essentially two models: 1) the first model is characterized by a collage of allochthonous terranes, each representing a distinctive geological history, and 2) the second model is characterized by a single autochthonous terrane representing a series of assemblages formed within the same geological environment, but within a tectonically and structurally complex environment. Until the mid 1980s, the tectonic models used for the development of the AGB were dominantly based on vertical tectonics proposed by Jensen (1985) and were similar to the current authochthonous model. However, the work of Jackson and Fyon (1991) and Jackson et al. (1994) in the late 1980s, proposed allochthonous models for the evolution of the AGB. Recently, Heather (1998) and Ayer et al. (1997, 1999a, 1999b) recognized that the western parts of the AGB contain multiple geochronologically distinct volcanic and sedimentary assemblages and suggested that this stratigraphy may be applicable to the remaining parts of the AGB. These assemblages cross former terrane boundaries, favouring an autochthonous model for the AGB. Furthermore, the geochemistry of the komatiites is uniform across former terrane boundaries, implying either the autochthonous model for the development of the AGB is correct, or that the terranes were originally located within the extent of the plume that is inferred to have formed the komatiites (Sproule et al. 2000).

PREVIOUS WORK IN PHYSICAL VOLCANOLOGY

Komatiites are ultramafic volcanic rocks that contain more than 18 wt % MgO on a volatile-free and olivine cumulate-free basis (Arndt and Nisbet 1982). Komatiitic basalts are defined as containing between 12 and 18% MgO on a volatile-free and olivine cumulate-free basis (Arndt and Nisbet 1982). Komatiitic basalts and particularly komatiites are generally only found in Archean greenstone belts (e.g., Abitibi, Canada; Yilgarn and Pilbara, Australia; Belingwe, Zimbabwe; Barberton, South Africa), although a few younger examples of komatiitic magmatism have been observed. These include the Proterozoic

Table 11.1. Main features of each assemblages of AGB established by Ayer et al.1999.

Assemblage	Age	Percentage of komatiite in the assemblage	Main Rock Types
Timiskaming	2685-2680 Ma	-	Conglomerates, sandstones, alkaline and calc-alkaline volcanic rocks
Porcupine	2698-2690 Ma	-	Turbidites and minor conglomerates
Blake River	2701-2698 Ma	-	Calc-alkaline and tholeiitic volcanic rocks
Kinojevis	2703-2701 Ma	-	Tholeiites and minor felsic volcanic rocks
Tisdale	2708-2703 Ma	~5 %	Tholeiitic volcanic rocks and komatiites Calc-alkaline felsic to intermediate volcanic rocks
Kidd-Munro	2717-2712 Ma	~12 %	Tholeiitic volcanic rocks and komatiites Calc-alkaline felsic to intermediate volcanic rocks
Stoughton-Roquemaure	2722-2720 Ma	~ 2 %	Mg-Fe tholeiitic basalt sequences with localized komatiites and felsic volcanic units
Pacaud	2745-2730 Ma	<< 1 %	Calc-alkaline and tholeiitic volcanic rocks and minor komatiites

Source: Ayer et al. 1997, 1999a, 1999b; Sproule et al. 2000 komatiitic basalts in the Cape Smith belt (Québec) and Phanerozoic komatiites on Gorgona Island, Columbia.

Komatiites were first described by Viljoen and Viljoen (1969) in the Komati River in the Barberton Greenstone Belt in South Africa. Since this time, an extensive amount of research has been undertaken to understand the genesis of komatiites. In particular, a large body of this research has been directed toward understanding komatiites that host Ni-Cu-PGE deposits. Recently, several researchers have recognized the importance of the volcanological processes to the genesis of mineralized komatiites (Lesher, Arndt and Groves 1984; Lesher 1989; Lesher and Campbell 1993; Hill et al. 1990; Hill et al. 1995; Barnes et al. 1999). There is an excellent understanding of the textural variability (Pyke, Naldrett and Eckstrand 1973; Arndt, Naldrett and Pyke 1977 and Donaldson 1982), cooling rate and crystallization (Donaldson 1974, 1976, 1982; Shore 1996), and physical properties (Huppert and Sparks 1985; Williams, Kerr and Lesher 1999) of komatiites, but volcanological processes and volcanic facies are less studied, and represent an important area of research.

Many komatiitic flows are internally layered with a spinifex-textured (A zone) in the upper part and a cumulus-textured (B zone) in the lower part of the flow (Pyke, Naldrett and Eckstrand 1973; Arndt, Naldrett and Pyke 1977; Donaldson 1982). The A unit may be further subdivided into the A1 (fractured upper chill zone / flow top breccia / microspinifex), A2 (randomly oriented spinifex), and A3 (coarse platy spinifex) zones. The B zone may be further subdivided into the B1 (aligned skeletal « hopper » olivine), B2 (medium- to coarse-grained cumulate), B3 (knobby cumulate), and B4 (fine-grained cumulate and basal chill) zones. All of the igneous textures result from the interaction of two fundamental processes: the nucleation of new crystals and the growth of the crystals. The crystal morphologies observed in komatiites may be represented by intermediates between two end-members: 1) polyhedral olivine crystals developed in slow cooling (lower supercooling and cooling rate) and 2) fine dendritic crystals developed during rapid cooling (high supercooling and cooling rate) (Donaldson 1976). The characteristic spinifex texture for which komatiites are well known and harrisitic texture result from intermediate cooling rates (Donaldson 1982; Hill et al. 1990). Although the A and B zones discussed above have been identified in many komatiite flows, Arndt, Naldrett and Pyke (1977), Arndt, Francis and Hynes (1979), Lesher, Arndt and Groves (1984), and Hill et al. (1990) have shown that the internal layering observed in komatiite flows is not always present, or may be only partially present.

A number of schemes may be utilized to classify komatiites. Discussed below are classification schemes based on lithofacies and volcanic facies.

Lithofacies Classification

This classification scheme (Lesher, Arndt and Groves 1984; Lesher 1989; Larson 1996) subdivides komatiitic lavas into different lithofacies as a function of olivine enrichment (fractional accumulation) and differentiation (fractional crystallization). This scheme (*see* Figure 11.1) yields four end members: undifferentiated non-cumulate (UN) flows, differentiated non-cumulate (DN) flows, undifferentiated cumulate (UC) flows, and differentiated cumulate (DC) flows (Larson 1996; Stone and Stone 2000). It may be also expanded to include inflated and non-inflated flows (Lesher 1999). This lithofacies classification is applicable in most field studies, although many localities contain more than one lithofacies.

Volcanic Facies

Komatiites form a wide range of volcanic facies including: vent facies, pyroclastic/epiclastic facies, lava lobe facies, lava pond facies, sheet flow facies, channelized sheet flows facies, channel-flow facies, and lava channel with overbank facies (Arndt , Francis and Hynes 1979; Lesher, Arndt and Groves 1984; Lesher 1989; Hill et al. 1995). Each volcanic facies may include a number of lithofacies and several internal textures within a flow unit. Volcanic facies mapping is particularly important as it facilitates recognition of favourable volcanic sequences which may host magmatic Ni-Cu-(PGE) sulphide

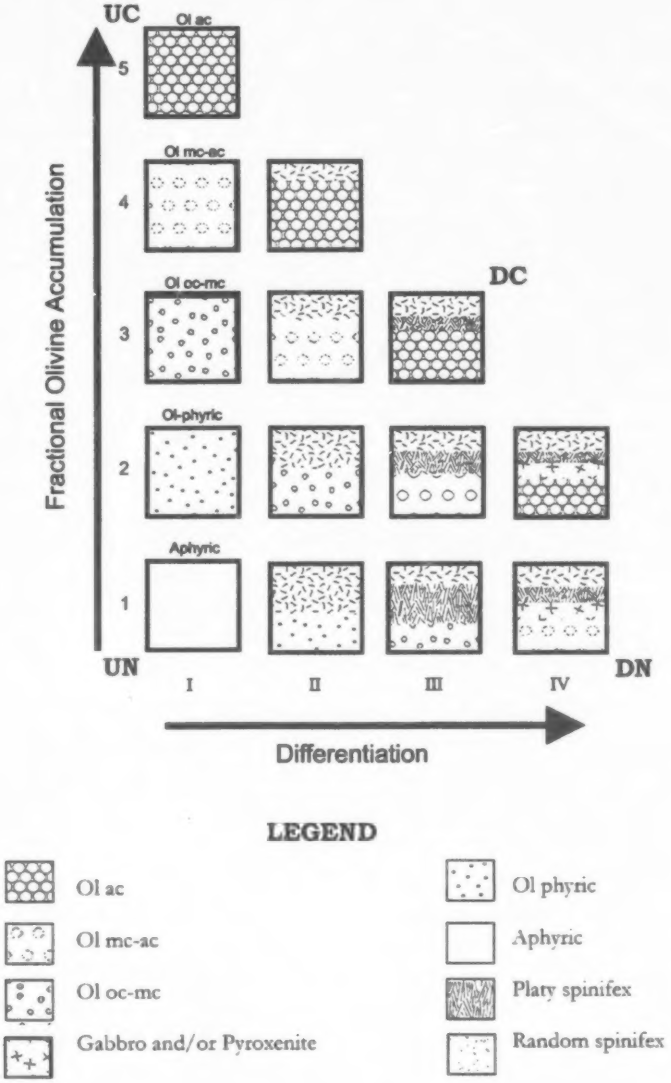

Figure 11.1. Schematic diagram showing the lithofacies variation in komatiitic flow units as function of olivine enrichment (fractional accumulation), *in situ* differentiation (fractional crystallization) (adapted from Stone and Stone 2000; Larson 1996; Lesher 1989; Lesher, Arndt and Groves 1984).

mineralization (Lesher 1989; Naldrett 1989; Barnes et al. 1999), thus aiding exploration for these deposits. The description of volcanic facies in komatiites is a relatively recent and controversial area of research. Many of the present models are based on basalt facies, and may be inappropriate for komatiites.

OBJECTIVES

The major aim of this study will be to establish the volcanic facies of komatiites in the AGB in order to constrain stratigraphic, tectonic, and metallogenic models. Specific goals of this project are to:

1. Define komatiite textures, lithofacies, and (if possible) volcanic facies within the AGB, using existing and new data acquired in this project. These data will be used to construct a lithofacies map for komatiites in the AGB. Using this map, we will determine if the physical volcanology (including lithofacies and facies type if appropriate) of the komatiites is consistent across terrane boundaries or changes across terrane boundaries.
2. Examine variations of lithofacies and volcanic facies within the stratigraphic framework defined by Ayer et al. (1997, 1999a, 1999b) to determine if there are temporal or spatial variations that occur in the physical volcanology of the komatiites.
3. Consider the implications of komatiite volcanic facies variation on tectonic models for the development of the AGB and for exploration for komatiite hosted Ni-Cu-(PGE) deposits.
4. Determine whether geochemical differences exist between different volcanic facies, and if the differences (or not) are consistent between assemblages.
5. Compare the geochemistry of similar volcanic facies of different ages.

METHODOLOGY

1. Compilation of published and unpublished data on lithology (e.g., komatiitic dunite, komatiitic peridotite, olivine-phyric komatiite, komatiite, and komatiitic basalt), textures (e.g., volcaniclastic, spinifex-textured, cumulate-textured), lithofacies (Lesher, Arndt and Groves 1984; Lesher 1989; Larson 1996) and volcanic facies (e.g., lava channels, sheet flows, lava ponds and lava lobes);
2. Field examination of critical areas to establish the volcanic facies. This will be restricted to areas with good outcrop (e.g., Shaw Dome; Boston Creek in Boston Township; Pyke Hill and Lava Lake in Munro Township; Alexo and Dundonald areas in Dundonald Township; Spinifex Ridge and Marbridge in La Motte Township), in addition to areas with extensive suites of recent diamond drill core (e.g., Munro and Dundonald Townships).
3. Facies analysis of these data to test and refine the physical volcanological models of Lesher (1989) and Hill et al. (1990) and, if necessary, develop new models.
4. Integration of physical volcanological and geochemical data to correlate and/or subdivide komatiites across the AGB. Utilization of these data to test and refine stratigraphic, tectonic and metallogenic models of Jackson and Fyon (1991), Jackson et al. (1994), Heather (1998), and Ayer et al. (1997, 1999a, 1999b).

CURRENT PROGRESS

During the past field season (2000), the initial aim of the field work was to gain familiarization with komatiites by visiting classic localities and to identify favourable areas in which to study the variation in volcanic facies in the AGB. The ultramafic rock successions visited included the Swayze Belt (Keith and Newton Twps), Shining Tree, the Barlett Dome (Serpentine Mountain), the Shaw Dome (Redstone pavement outcrop in Eldorado and Adams Twps), Destor–Porcupine Fault Zone (Guibord Twp), Kidd-McCool assemblage (Pyke Hill, Lava Lake, Alexo, and Dundonald Beach), Round Lake Dome (Boston Creek and Otto Lake), Lake Abitibi (Roquemaure area), and the La Motte Dome (Spinifex Ridge).

Furthermore, detailed sampling of diamond drill core through the Lava Lake sequence (Arndt, Naldrett and Pyke 1977) near the Potter Mine in Munro Township was initiated. Detailed mapping of surface exposures of the Lava Lake sequence will begin in September 2000.

SUMMARY

The aim of this project is to examine the spatial and geochemical variations in volcanic facies of komatiite flows within the AGB, and specifically in the Kidd–Munro Assemblage, to test and redefine, if appropriate, the stratigraphic, tectonic and metallogenic models of Jackson and Fyon (1991), Jackson et al. (1994), Heather (1998), and Ayer et al. (1997, 1999a, 1999b). In addition, the integration of physical volcanology and geochemical data will test and refine the volcanic facies models of Hill et al. (1990, 1995) for komatiite flows.

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12. Project Unit 00-011. Structural Investigations of the Echo Bay and International Falcon Properties in Ogden Township

É. Dinel[1] and K. Benn[1,2]

[1]Department of Earth Sciences, University of Ottawa, Ottawa, ON
[2]Ottawa-Carleton Geoscience Center, Ottawa, ON

INTRODUCTION

The objective of this project is to further our understanding of the deformational history within and adjacent to the Destor–Porcupine deformation zone in the area southwest of Timmins, Ontario. The study area includes properties belonging to Echo Bay Mines Ltd. and International Falcon Resources Ltd., and it is situated in the central part of Ogden Township, 6 km southwest of Timmins. It lies immediately to the south of the western extension of the Porcupine–Destor deformation zone as it appears on the geological map of Pyke (1982). The rocks in the study area are generally intensely deformed, and we interpret that they in fact lie within the Destor–Porcupine deformation zone.

During the summer of 2000, detailed geological mapping was carried out on a series of traverses and in trenches. Structural profiles and structural petrographic studies will be completed during the 2000–2001 academic year. In this report we summarize the field work component of the project.

GEOLOGY

The geological units of the study area are composed mainly of deformed and altered ultramafic volcanic rocks of the Tisdale assemblage (2708 to 2702 Ma, Ayer et al. 1999) and of the stratigraphically underlying Deloro assemblage (2730 to 2725 Ma, Ayer et al. 1999) that is predominantly composed of intermediate to felsic crystal tuffs. The Deloro assemblage also includes subordinate chert-rich banded iron formation.

Two alteration facies are identified in the Tisdale ultramafic volcanic rocks; a highly carbonatized fuchsite-chlorite schist, and a less carbonatized talc-chlorite schist. Relicts of spinifex textures are locally preserved in both alteration facies, and they contain quartz-carbonate stringer zones with associated pyrite mineralization.

Depositional contacts between intermediate to felsic tuffs and ultramafic rocks were identified in several outcrops. This observation leaves open the possibilities that 1) the original contact between the Tisdale and the Deloro assemblages was depositional, and 2) that the transition from predominantly intermediate to felsic volcanism (Deloro) to ultramafic volcanism (Tisdale) was transitional, resulting in the intercalation of tuffs and ultramafic flows.

STRUCTURAL GEOLOGY

Deformation in the study area is manifested by three distinct generations of tectonic structures. The relative timing relationships of the three generations of structures are evident in the field, and we assign them to three deformation events, D_1 through D_3.

D_1 Structures

D_1 structures include a penetrative S_1 foliation that strikes broadly east–west, and that has variable dips ranging from shallow to subvertical due to post-D_1 folding. The east-northeast-striking S_1 foliation (Figures 12.1a and 12.2a) is axial planar to F_1 folds of the depositional surfaces in the volcanic rocks and in subordinate sedimentary horizons. F_1 folds were observed within the Deloro iron formation (Figure 12.1b) where they have upright axial surfaces and plunge to the southwest (Figure 12.2b). The variations in dip of S_1 (Figure 12.2a) may be attributed to post-D_1 folding.

Quartz-carbonate stringers and quartz veins with orientations that are close to the strike of S_1 are boudinaged whereas stringers oriented at high angles to S_1 are folded (Figure 12.1a), suggesting the stringers underwent the D_1 (broadly) north–south directed shortening that gave rise to the S_1 foliation and F_1 folds.

D_2 Structures

D_2 is principally characterized by a sub-horizontal to shallowly dipping (usually less than 30° dip angle, Figure 12.2c) millimetre-scale to centimetre-scale folds (crenulations), and in some outcrops by metre-scale folds, of the S_1 foliation. Locally, an S_2 crenulation (disjunctive) cleavage is developed (Figure12.1c) which is axial planar to the F_2 folds. Because the S_2 cleavage has shallow dips (Figure12.2c), it is best observed on steeply dipping outcrop faces. Where they are observed on S_1 cleavage surfaces, the hinges of the F_2 crenulations define a shallowly plunging $L_{1/2}$ intersection lineation. F_2 fold axes are subhorizontal and trend east-northeast (Figure 12.1d).

One of the best exposures of F_2 folds is within the Bianchi quarry, located on the Echo Bay Mines Ltd. property. The folds have half-wavelengths of approximately 3–4 m. The axial surfaces have shallow dips and the fold hinges plunge shallowly to the west-southwest. In that exposure, (at least) one generation of quartz-carbonate veins are subparallel to the folded S_1 foliation (Figure 12.1c), and therefore predate F_2. Another generation (or generations) of quartz-carbonate veins are parallel to the axial surface of the F_2 folds.

D_3 Structures

D_3 structures are subvertical, north to 030° striking F_3 folds (Figure 12.1d) and S_3 crenulation cleavage (Figures 12.1e and 12.2e). The S_3 cleavage clearly deforms the S_2 cleavage (Figure 12.1e). The F_3 folds have axial plunges dependent on the orientation of S_1 prior to F_3 folding. Where S_1 was dipping to the northeast, the F_3 fold axes plunge to the northeast, and where the S_1 foliation had a southwest dip direction, the F_3 folds dip to the southwest (Figure 12.1d). Outside of the study area, within Bristol Township (Holmer Gold Mines Ltd. property), F_3 folds and S_3 cleavage are locally concentrated within well defined tabular or lenticular zones that we interpret as D_3 shear zones (Figure 12.1f). The degrees of strain and displacement on the zones appear to be quite low.

DISCUSSION

The main results of this study, thus far, are the recognition of depositional contacts between rocks possibly belonging to the Deloro and Tisdale assemblages, and the documentation of three generations of ductile deformation (D_1 to D_3). It is of interest to note that further to the east, in Holloway Township, a

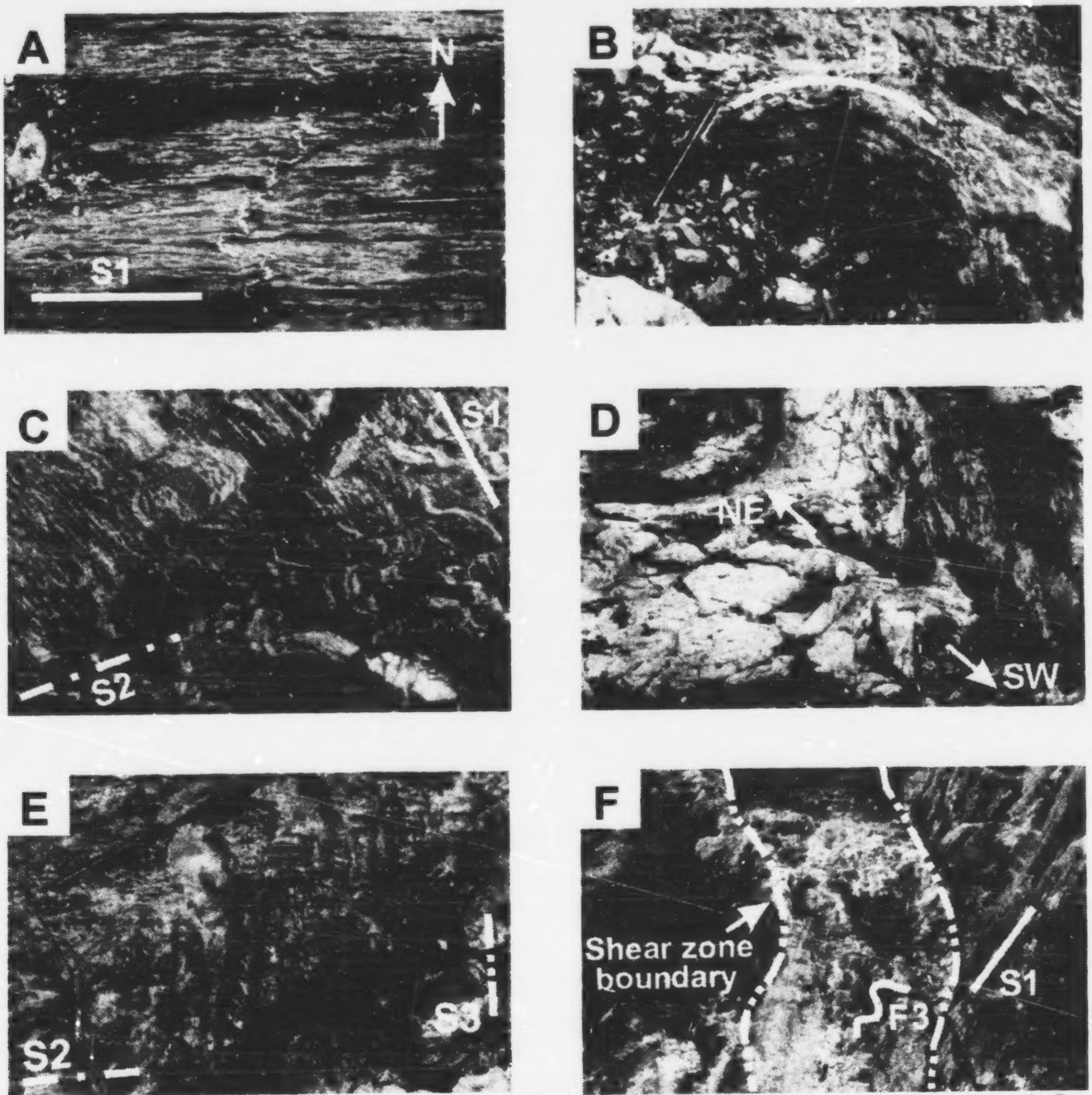

Figure 12. 1 a) East striking S_1 cleavage in ultramafic volcanic rocks. Note the severely shortened north striking quartz vein. Pen for scale. **b)** F_1 fold hinge in chert-rich banded iron formation. Pen for scale. **c)** Axial-planar S_2 crenulation cleavage in hinge zone of an outcrop-scale F_2 fold. Quartz-carbonate veins are parallel to S_1. The traces from the top left to the bottom right in the photo are cut marks from quarrying. **d)** A doubly-plunging metre-scale F_3 fold. Arrows indicate plunges of the fold hinge. **e)** Subvertical S_3 crenulation cleavage overprinting the subhorizontal S_2 crenulation cleavage. Pen for scale. **f)** F_3 folds of the S_1 cleavage within a D3 shear zone (Bristol Township). Shear zone is about 1 m wide.

very similar deformational history has been documented within the Porcupine–Destor deformation zone (Luinstra and Benn 1999, 2000). Further structural analyses in the present study area and elsewhere along the Porcupine–Destor deformation zone may reveal a continuity in its structural evolution, and should provide important information on the origin and significance of this regional scale structure.

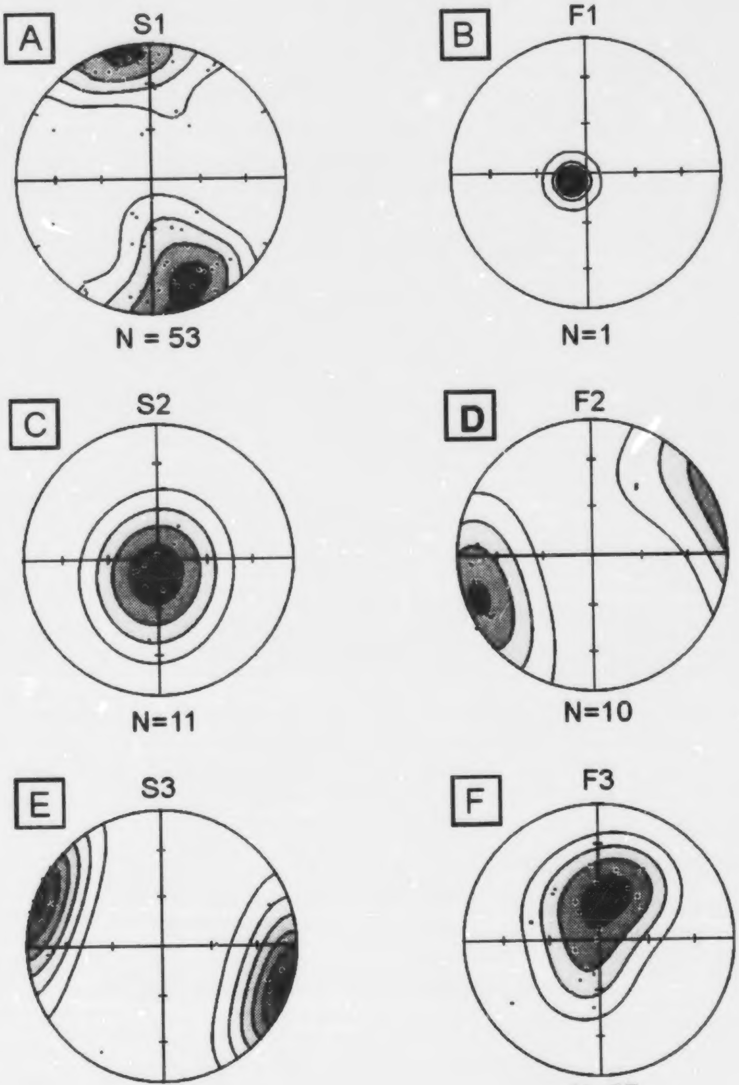

Figure 12.2. Lower-hemisphere equal-area projections of structural measurements for the study area.

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13. Project Unit 95-034. An Integrated View of Western Superior Crustal Evolution: Highlights of 2000 NATMAP Studies

J.A. Percival[1], A.H. Bailes[2], M.T. Corkery[2], B. Dubé[3], J.R. Harris[1], V. McNicoll[1], D. Panagapko[1], J.R. Parker[4], N. Rogers[1], M. Sanborn-Barrie[1], T. Skulski[1], D. Stone[4], G.M. Stott[4], P.C. Thurston[4], K.Y. Tomlinson[1], J.B. Whalen[1] and M.D. Young[5]

[1] Geological Survey of Canada, 601 Booth St. Ottawa, ON, K1A 0E8
[2] Manitoba Geological Survey, 360–1395 Ellice Ave. Winnipeg, MB, R3G 3P2
[3] Geological Survey of Canada, 2535, boul. Laurier, C.P. 7500, Sainte-Foy, Quebec, G1V 4C7
[4] Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, ON, P3E 6B5
[5] Department of Geological Sciences, Queen's University, Kingston, ON, K2B 6N1

INTRODUCTION

The western Superior NATMAP project aims to provide a modern geoscience synthesis of northwestern Ontario and eastern Manitoba using resources of the Federal, Ontario and Manitoba geological surveys (GSC, OGS and MGS, respectively), working at a variety of detailed and regional map scales. Key areas have been selected to address questions regarding relationships between Mesoarchean and Neoarchean sequences of the western Superior Province (Figure 13.1; Percival et al. 1997), through new mapping, geochemistry, geochronology and GIS-based compilation. In 2000, the fourth year of field operations, focus was on the Uchi Subprovince (Figure 13.2) at the southern margin of the Mesoarchean North Caribou terrane, with continued work on the Wabigoon and Sachigo subprovinces.

Below, we present highlights of 2000 field and ongoing laboratory studies. Further syntheses in the form of a series of compilation maps will be released over the next year.

UCHI SUBPROVINCE

Lake Winnipeg Area

A collaborative mapping program in the Black Island area (*see* Figure 13.2) followed initial reconnaissance studies (Bailes 1999; Percival and Whalen 2000). At least three distinct supracrustal sequences are present, in addition to a *ca.* 3 Ga basement complex.

BASEMENT COMPLEX

Hornblende-biotite tonalite of the east shore complex represents basement to the Lewis–Storey assemblage. These coarse-grained, homogeneous rocks with characteristic blue quartz resemble tonalitic units dated in the vicinity at 3.006–2.998 Ga (Ermanovics 1970, 1981; Krogh et al. 1974; Turek and Weber 1994; V. McNicoll, unpublished data). North-trending chlorite-grade shear zones (D_1) carry distinctive shear band fabrics indicating dextral strike-slip motion.

The east shore complex and English Lake complex to the east (3.006–2.992 Ga) share distinctive geochemical features. Rocks ranging in composition from tonalite through diorite and gabbro have multi-element profiles with modest negative Ti and Nb anomalies, and strongly depleted Th and Rb. These primitive arc characteristics may be the product of an ultradepleted mantle source.

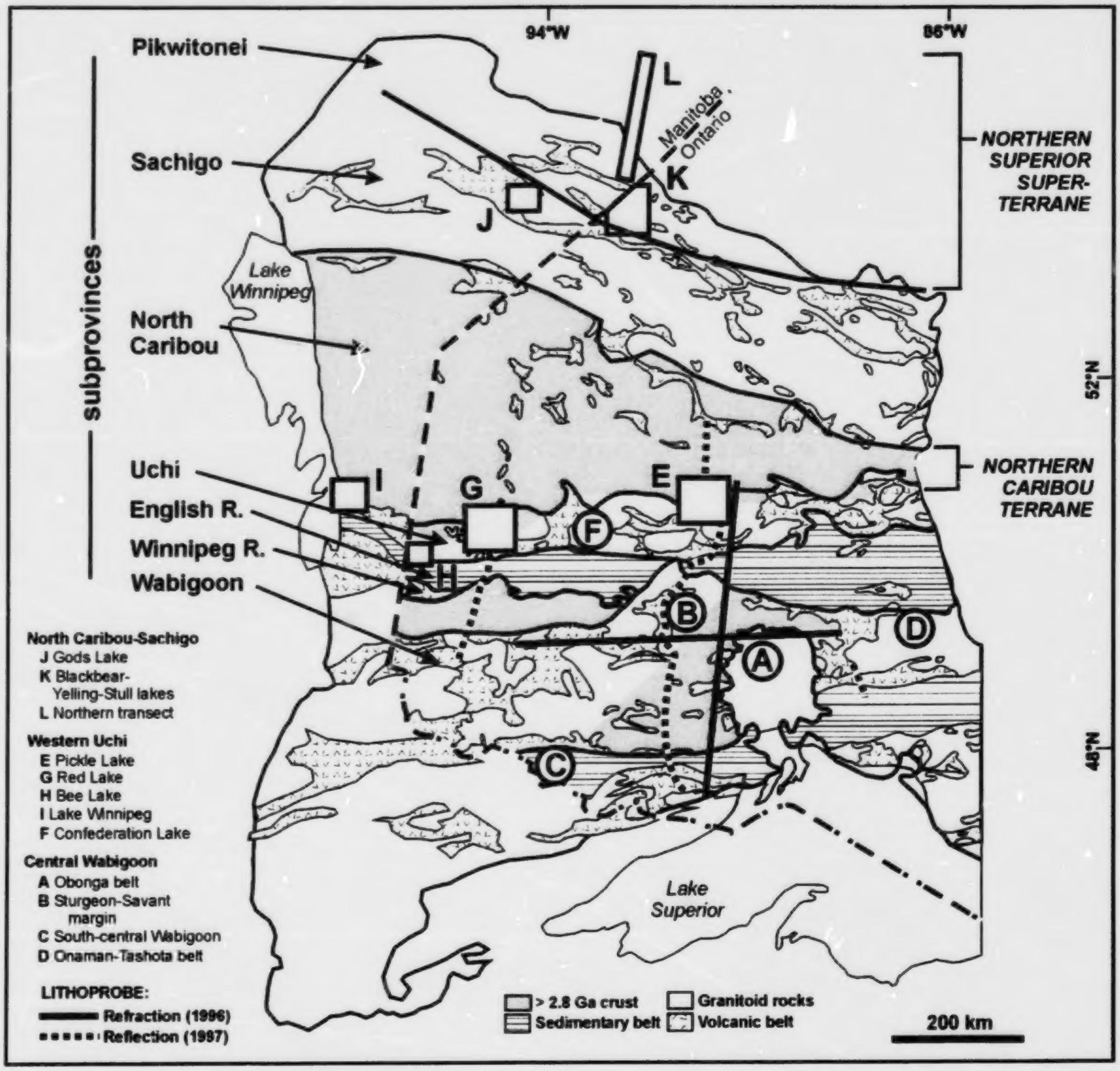

Figure 13.1. Schematic tectonic map of the western Superior Province showing locations of areas under study.

LEWIS-STOREY ASSEMBLAGE

A west-facing sedimentary-volcanic sequence lies unconformably above the east shore complex and may represent a Mesoarchean rift succession (Thurston and Chivers 1990). A similar quartzite-carbonate-iron formation-komatiite package has been dated at Wallace Lake, 70 km to the east, at <3.0>2.92 Ga (Poulsen et al. 1996; Sasseville and Tomlinson 2000; Tomlinson and McNicoll, unpublished data, 2000). The unconformity, documented at six localities over 30 km of strike length, separates tonalite from a unit of coarse, massive to thick-bedded grit with a chloritic matrix. Thinly laminated, fine-grained quartz arenite occurs in units up to a few metres thick, in association with muscovite-rich schist, aluminosilicate-bearing schist and talc schist. Overlying komatiite has spinifex with radiating clinopyroxene up to 20 cm long (*see* Figure 5 in Percival and Whalen 2000). Associated iron formation consists of centimetre-scale layers of carbonate, chert, magnetite and sericite schist. Mafic sills up to 15 m thick intrude both the basement and cover sequence adjacent to the unconformity.

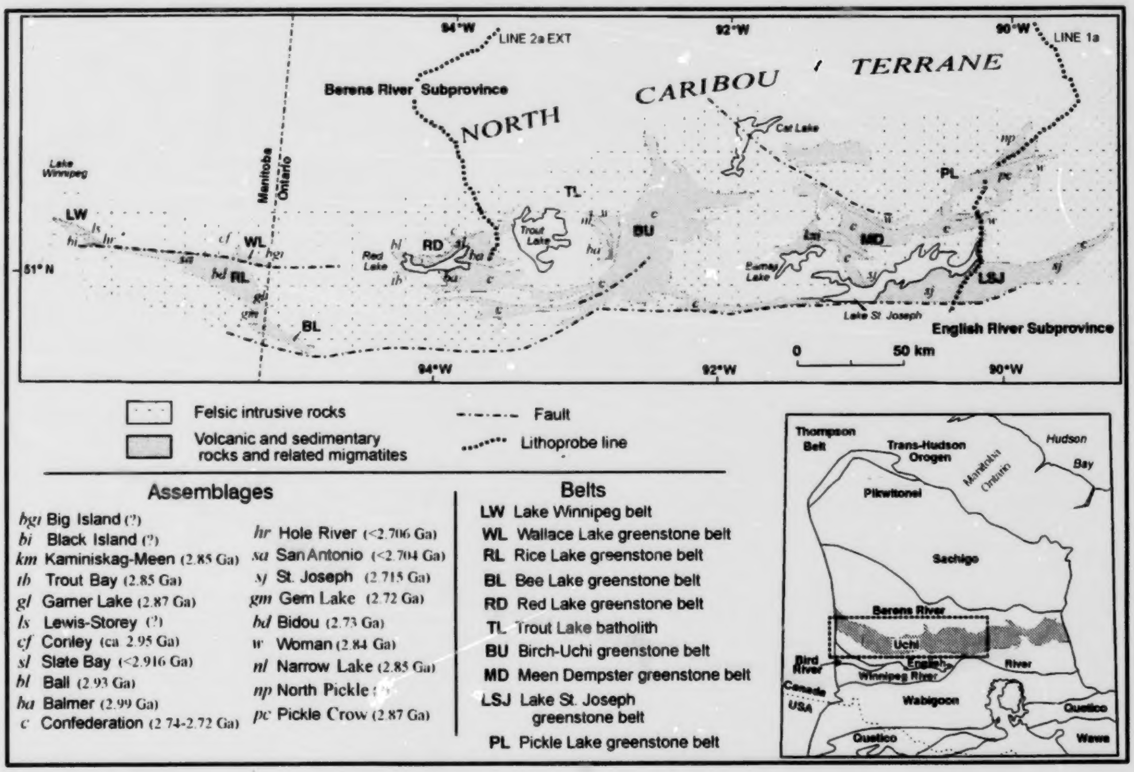

Figure 13.2. Generalized tectonic map of the western Uchi Subprovince showing locations of assemblages discussed in the text (modified after Stott and Corfu 1991; Sanborn-Barrie et al. 2000).

BLACK ISLAND SEQUENCE

The homoclinal, west-facing Black Island sequence comprises two basalt-dominated packages (Bailes and Percival 2000). A lower stack of thick massive flows, the Gray Point sequence, has flat (*ca.* 5× chondrites) multi-element profiles with LREE, Th, Nb depletion. It is separated by a thin volcaniclastic unit from an upper unit of pillow basalt, the Drumming Point sequence, of calc-alkaline affinity. A thin unit of lithic wacke caps the sequence. Ermanovics and Wanless (1983) reported an age of 2732 Ma for Black Island rhyodacite, however the relationship between this east-facing outcrop located structurally beneath the basalt, and the main Black Island sequence, is not known.

HOLE RIVER SEQUENCE

Pink and grey arkose and rare conglomerate of the Hole River sequence occur mainly on islands. These fine to coarse-grained sandstone contain detrital zircon grains with ages as young as 2706 Ma (V. McNicoll and J.A. Percival, unpublished data). Conglomerate clast types include massive, leucocratic granite, supporting a Timiskaming-type setting.

All units carry a penetrative, north-trending, steeply west-dipping S_1 foliation and widespread concordant D_1 high-strain zones up to 40 m wide. Shear-sense indicators, including late D_1 "Z" folds (F_{1a}), suggest dextral kinematic sense. In the eastern part of the area, ductile D_1 fabrics are truncated by sheets and plutons of biotite granodiorite that may be correlative with granodiorite dikes with a poorly constrained *ca.* 2715 Ma age (Krogh et al. 1974). Southwest-trending S_2 crenulations are common in thinly laminated high-strain (D_1) zones. A steeply dipping, east-trending zone of dextral greenschist-facies high strain (D_3) forms the linear shoreline in the vicinity of Seymourville. It translates the basement Lewis–Storey unconformity approximately 7 km to the west, into the Pelican Harbour area.

A poorly preserved sedimentary-volcanic sequence lies along the southern margin of an east-trending body of hornblende-biotite tonalite in the Wanipigow River area. Both the tonalite and supracrustal rocks resemble those in eastern Lake Winnipeg, although an unconformity was not observed. The tonalite is bordered to the south by a grit unit up to 10 m thick and is overlain by fine-grained, thinly laminated siliceous siltstone. Sporadic magnetite-chert and hematite-chert ironstone is also present at this structural level. Gabbroic sills with minor serpentinite schist layers occur structurally above the iron formation, as well as within the tonalite.

A working hypothesis involves deposition of the Lewis–Storey rift sequence on the western margin of 3 Ga basement of the North Caribou terrane, with subsequent spreading recorded by mafic sill emplacement. The margin collapsed as the Black Island sequence was juxtaposed, probably in a strike-slip regime *ca.* 2.72 Ga. Hole River sediments were deposited in strike-slip basins during continued D_1 oblique convergence. Waning deformation became focussed in shear zones during D_2 and D_3 transcurrent shear events.

Bee Lake Greenstone Belt

The Bee Lake greenstone belt (Figures 13.1, 13.2), which straddles the Manitoba–Ontario border, represents the southeastern extension of the Rice Lake belt. Due to its limited (float plane) access and relatively small size (*ca.* 170 km^2), this belt has not been mapped in detail since Shklanka (1967). Consequently, no geochronology or geochemical data are available.

The Bee Lake greenstone belt consists of a relatively simple volcano-sedimentary sequence that has undergone two ductile deformation (folding) events (referred to herein as D_1 and D_2), as well as subsequent brittle-ductile faulting. These rocks have been intruded by several generations of dikes and plutons, from which the timing of deformation events will be constrained.

The volcano-sedimentary sequence consists of a basal suite of probably calc-alkaline basaltic flows, pillow basalt and pillow breccia, which are overlain by interbedded felsic volcanic and clastic sedimentary rocks. The felsic volcanic rocks are predominantly epiclastic volcanic breccia, whereas the sedimentary rocks typically consist of arkosic sandstone and conglomerate. Locally, the conglomerate contain boulder-sized clasts of granodiorite that have undergone little or no pre-entrainment deformation.

D_1, the main deformation event in the belt, consists of at least three pulses of folding, interspersed with intrusions of tonalitic dikes that are generally transposed nearly parallel to the S_1 cleavage. D_1 folds trend west-northwest with a major east-southeast-plunging syncline centred on Bee Lake, and a corresponding anticline centred on Odd Lake. D_2 is synchronous with intrusion of the Wingiskus Lake granodiorite pluton, which forms the core to a dome. D_1 and D_2 structures are cut by late granodioritic intrusions, such as the Reahil Lake pluton. All rocks are cut by conjugate sets of brittle faults that are probably related to movement of the Sydney Lake – Lac St. Joseph Fault, which marks the southern margin of the belt.

Previously the Bee Lake greenstone belt has been correlated with the Confederation assemblage. However, the noticeably different rock types and stratigraphy between this region and the type section for the Confederation assemblage in the Birch–Uchi greenstone belt and its extension in the Red Lake greenstone belt suggest that this correlation may not be valid. Rather, the Bee Lake belt may correlate with the *ca.* 2.720 Ga Gem Lake subgroup of the adjacent Rice Lake greenstone belt.

Red Lake Greenstone Belt

The second field season of western Superior NATMAP activities in the Red Lake greenstone belt (cf. Sanborn-Barrie et al., 2000; Figure 13.2) focussed on integrating geological mapping with new and previously available lithogeochemical, geochronological and GIS data to further advance an understanding of: 1) the interplay between magmatism, alteration, deformation and mineralization; 2) the relationships between Meso- and Neoarchean assemblages; and 3) the tectonic setting of the belt through 300 million years of Archean history. Collectively, these data highlight a history of episodic magmatic activity and sedimentation along the south margin of the North Caribou protocraton, and orogenic activity that culminated in collision with the Winnipeg River protocraton during a *ca.* 2.72 Ga phase of the Kenoran orogeny.

The earliest magmatism is represented by the *ca.* 2.99 Ga Balmer assemblage which is dominated by submarine, high TiO_2 tholeiitic basalt that range from light rare earth element (LREE) and large ion lithophile (LIL) depleted, to slightly enriched with small positive Th/Nb anomalies. Komatiite (olivine spinifex) and komatiitic basalt (pyroxene spinifex) are LREE-depleted with positive Th/Nb anomalies. In contrast, komatiite and basalt of the *ca.* 2.94–2.92 Ga Ball assemblage are associated with voluminous intermediate to felsic volcanic rocks, have calc-alkaline affinities, low TiO_2 contents and show a greater degree of LREE and LIL enrichment. Resurgence of calc-alkaline magmatism and volcaniclastic deposition at 2.894 Ga, followed by quiescent marine conditions is recorded by the Bruce Channel assemblage. New field, geochronological and geochemical data from the southwest part of the belt indicate the presence of the Trout Bay assemblage (*see* Figure 13.1), consisting of *ca.* 2.85 Ga intermediate tuff and marine siliciclastic and chemical sediments overlain by coarse fragmental rocks and submarine, low TiO_2 tholeiitic basalt that are strongly depleted in LREE and LILE. Finally, new data allow subdivision of the Neoarchean Confederation assemblage into the 2.748–2.742 Ga McNeely sequence, a shallow marine, calc-alkaline mafic to felsic succession, the overlying 2.744–2.739 Ga Heyson sequence of tholeiitic basalt, F_3 rhyolite and minor calc-alkaline volcanic rocks; and the younger *ca.* 2.733 Ga Graves sequence comprising an intermediate calc-alkaline volcano-plutonic complex.

This protracted history of magmatic activity is punctuated by sedimentary episodes involving deposition of locally derived clastic detritus and precipitation of chemical sediments. Compositionally immature clastic rocks occur within the Balmer, Bruce Channel and Trout Bay assemblages, in contrast to compositionally mature fuchsitic quartz arenite and conglomerate interstratified with *ca.* 2.94–2.925 Ga felsic volcanic rocks of the Ball assemblage and forming the post-2.912 Ga Slate Bay assemblage that disconformably overlies Balmer basalt. A regionally extensive unit of polymictic conglomerate marks the interface between Mesoarchean and Neoarchean strata, consistent with an emerging view that the main stages of crustal growth in the Red Lake belt from *ca.* 3 Ga to 2.7 Ga were primarily depositional, not tectonic.

The Red Lake greenstone belt is polydeformed with an early (pre-2.748 Ga) nonpenetrative deformational event (D_0) and at least two recognizable generations of ductile structures (D_1, D_2) imposed after *ca.* 2.742 Ga volcanism. Early deformation involved overturning of Balmer pillowed basalt, as documented by opposing facing on either side of the regionally extensive angular unconformity in the Madsen and central Red Lake areas, and is interpreted to have involved recumbent folding. The main stages of penetrative deformation resulted in two sets of folds (F_1 and F_2), established by opposing younging and structural facing. Planar and/or linear fabrics associated with D_1 trend northerly and are locally recognized throughout the belt, whereas widespread, weakly to moderately developed, L-S fabrics associated with F_2 folds (D_2) trend east to northeasterly. The timing of deformation is established by field relationships involving the 2.718 Ga Dome Stock which contains foliated xenoliths of local country rock, but is itself weakly to moderately foliated with a throughgoing northeast-striking fabric, characteristic of the regional S_2 foliation. Deviation in the orientation of interpreted D_2 fabrics from the regional (east- to northeast-striking) S_2 trend, to an east-southeasterly striking low-strain corridor between Cochenour and Balmertown may have evolved through shifting local boundary conditions in the eastern Red Lake belt if, as predicted, the Trout Lake batholith (*see* Figure 13.1) includes a major phase of *ca.* 2.72 Ga magmatism. Localization of strain into a belt-scale system of conjugate shear zones (cf. Andrews et al., 1986) was not substantiated during this study.

The majority of gold deposits in the Red Lake district are the end-product of hydrothermal replacement and constitute atypical greenstone-hosted gold types. The Campbell–Red Lake deposit consists mainly of early to syn-D_2 quartz-arsenopyrite-rich selective replacement zones of colloform-crustiform iron-carbonate veins and breccia. These silicified carbonate veins are mainly hosted by heterogeneously foliated basalt within the east-southeast-trending D_2 strain corridor informally designated the mine trend. The Madsen deposit is an amphibolite-grade, disseminated-replacement style gold deposit hosted by mafic volcaniclastic rocks. On the basis of style and mineralogy, this deposit has been interpreted as an Au-rich skarn-like deposit (Dubé et al. 2000). All of the major Red Lake deposits are proximal to a regionally extensive angular unconformity between the *ca.* 2.99 Ga Balmer and *ca.* 2.74 Ga Confederation assemblages.

The district has been affected by large-scale hydrothermal alteration systems resulting in strong to intense calcite carbonatization that affects rocks of the Balmer, Ball, Bruce Channel and Confederation assemblages. Less extensive areas of strong to intense ferroan-dolomite alteration enclose the majority of gold deposits in the greenstone belt and represent proximal alteration envelopes that affect the Balmer, Ball and Confederation assemblages. The proximal zones are characterized by a greater volume of ferroan-carbonate veins and disseminated sulphide mineralization than in calcite-altered areas. Potassic alteration in the form of pervasive biotitization occurs in proximal alteration zones. Metamorphosed proximal alteration zones are characterized by a diverse assemblage of aluminosilicate minerals such as andalusite, staurolite, garnet and chloritoid.

Carbonatized mafic metavolcanic rocks adjacent to the Killala–Baird batholith have been metasomatized and pervasively replaced by a calc-silicate assemblage of diopside, orange garnet, epidote, tremolite, calcite and quartz. Diopside veins also cut and replace early ferroan-carbonate veins and are associated with gold zones at Madsen. Field observations and mapping indicate that diopsidic veins and skarnification are related to the Killala–Baird batholith and that the batholith may be related to the formation of the Madsen gold deposit. This observation indicates that a previously unrecognized skarn zone, situated along the margin of the batholith, is a prospective exploration target for Madsen-type gold mineralization.

The tectonic evolution of the Red Lake greenstone belt appears to have involved *ca.* 2.99 Ga plume-related rifting followed by development of a *ca.* 2.94–2.92 Ga calc-alkaline arc complex (cf. Tomlinson et al. 1998; Hollings et al. 1999). Intercalation of komatiite within this arc complex may reflect rifting and/or impingement of a plume in a subduction zone setting (Hollings et al. 1999). Renewed arc volcanism at 2.89 Ga followed by tectonic quiescence and subsidence across the continental margin may reflect a transition from orthogonal convergence (arc volcanism) to transform faulting (magmatic quiescence). This may have led to accretion of the 2.85 Ga Trout Bay island arc – back arc complex with the southern North Caribou margin resulting in pre- 2.75 Ga recumbent folding, uplift and sedimentation. Unconformably overlying rocks record a Neoarchean history of renewed emergent arc volcanism at 2.75–2.74 Ga (McNeely sequence), followed by subsidence and intra-arc rifting at 2.74 Ga (Heyson sequence). A final phase of Andean-style arc magmatism at *ca.* 2.73 Ga, recorded at Red Lake (Graves sequence) and throughout the Berens arc, is diachronous along the margin between 2.73 Ga and 2.72 Ga. This is interpreted to reflect subduction beneath the southern North Caribou margin leading to collision of the Winnipeg River protocraton at *ca.* 2718 Ma during the Uchian phase of the Kenoran orogeny.

A cooperative GIS/database project involving the GSC, OGS and mineral industry partners is underway in the Red Lake greenstone belt to assemble, integrate and release hard copy maps and a CD-ROM comprising all available digital and analog geoscience data. To date, emphasis has been on compiling public domain information. The main geoscience themes compiled to date include: bedrock and surficial geology, regional lithogeochemistry, diamond drilling and other types of mineral exploration assessment work, airborne magnetic, electromagnetic and gamma ray data, and Landsat imagery. A preliminary release of data in ArcInfo, ArcView and MapInfo formats is scheduled for early December. A short field program was conducted in June 2000, to sample areas of anomalous carbonate, sericite and silica alteration based upon preliminary analysis of lithogeochemical data. Analyses will be compared with the regional dataset to assess possible patterns. The data will be integrated with other exploration tools and criteria (regional unconformities, fault zones, etc.) in the GIS to produce mineral prospectivity maps.

Confederation–Birch–Uchi Greenstone Belt

Additional geochronology is currently being conducted in the Confederation–Birch–Uchi greenstone belt (*see* Figure 13.2) in an attempt to constrain whether the *ca.* 2.84 Ga Woman assemblage is present at its type locality. Initial attempts to directly date this sequence failed, whereas chemically and petrographically indistinguishable rocks adjacent to the type locality have yielded dates typical of the Confederation assemblage (*ca.* 2.74 Ga). However, evidence for a pre-Confederation assemblage has been obtained in the form of a *ca.* 2.81 Ga quartz-feldspar-porphyry dike along the western shore of Woman Lake (V. McNicoll, unpublished data, 2000). Hence the likely volcanic stratigraphy for the Birch–Uchi greenstone belt is as follows: i) Balmer assemblage – andesitic to rhyolitic volcanism (2.989

to 2.975 Ga), separated by an early (D_0) deformation event, from ii) Narrow Lake assemblage – tholeiitic pillow basalt that unconformably overlie the Balmer assemblage (bracketed between 2.975 and 2.832 Ga; most likely *ca.* 2.855 Ga from comparison to the Red Lake greenstone belt); iii) Woman assemblage – pillow basalt overlain by ignimbritic rhyolites that disconformably overlie the Narrow Lake assemblage (bracketed between 2.88 and 2.81 Ga); and iv) Confederation assemblage – three petrographically, chemically and spatially distinct belts of mafic to felsic volcanism (*ca.* 2.74 Ga).

Pickle Lake Greenstone Belt

Field work in the Pickle Lake area (*see* Figure13.2) during the 2000 field season was aimed at testing the hypotheses that the lithotectonic assemblages comprising the Pickle Lake greenstone belt were either built on, or accreted to, the south margin of the *ca.* 3.0 Ga North Caribou terrane protocraton. Stott's (1996) summary of stratigraphic, structural, and geochronological studies favoured an accretionary model for southern part of the Pickle Lake greenstone belt. However, new results to the west (Birch–Uchi and Red Lake greenstone belts; Rogers et al. 2000; Sanborn-Barrie et al. 2000) have established that the main stages of crustal growth were primarily depositional, not tectonic.

Of the four lithotectonic assemblages comprising the Pickle Lake greenstone belt, concerted effort was directed at the two northerly assemblages, the North Pickle and Pickle Crow. The North Pickle assemblage is composed dominantly of massive and pillowed basalt flows, interbedded with carbonate-siliceous banded iron formation and minor clastic units, as well as sill-like mafic intrusive sheets. The assemblage was interpreted as the southern extension of the *ca.* 3.0 Ga McGruer assemblage of the North Caribou belt based on aeromagnetic patterns (Stott 1996). However, limited facing directions determined from pillow tops indicate a northwesterly younging direction, opposite to that of the McGruer assemblage. The Pickle Crow assemblage consists of massive to pillowed basaltic flows, dacitic pyroclastic flows, carbonate-siliceous banded iron formation interbeds which, macroscopically, are very similar to those of the North Pickle assemblage, and a locally derived polymictic conglomerate where the majority of clasts are of the same provenance. Limited facing directions determined from grading in the conglomerate and sparse pillow tops indicate local northwesterly younging, but tight folds preclude attaching regional significance. Quartz porphyry sills intruded the basaltic sequence and zircon grains from one yielded a crystallization age of 2.86 Ga and an inherited age of 2.892 Ga (Corfu and Stott, 1993).

Two major deformation events and an early localized strain event are recorded in the two northerly assemblages. The main regional event, D_1, is defined by a belt-wide, weakly to moderately developed, northwest-dipping foliation generally parallel to stratigraphic contacts, with similar trends in both assemblages. In the North Pickle and southern Pickle Crow assemblages, S_1 fabric is weakly developed. It is more prominent in the north central Pickle Crow area, in a zone of tight F_1 folding. The D_1 fabric is overprinted by contact strain aureoles, here termed D_2, associated with *ca.* 2740 Ma felsic intrusive plutons and stocks. D_2 intensity is variable across the belt, ranging from a moderate crenulation in the east, to strong, amphibolite-grade flattening in the west. Evidence of pre-D_1 deformation is found in the north-central Pickle Crow area, where D_1 fabrics related to F_1 folds crenulate an older foliation developed in carbonatized basalt. The pre-D_1 fabric is cut by *ca.* 2.86 Ga quartz porphyry sills, indicating localized Mesoarchean deformation. The aeromagnetic pattern shows that stratigraphic and fold axis trends are similar in both assemblages across the assumed boundary. Also, the boundary itself is at an angle ($\sim 30^0$ clockwise) to stratigraphic contacts, and fold axes are not parallel to the fabric in the Pickle Crow assemblage, as would be predicted if the Pickle Crow assemblage had accreted onto the southern margin of the North Pickle assemblage.

Without absolute age constraints and in light of the above observations, evidence is insufficient to separate the North Pickle and Pickle Crow assemblages into distinct lithotectonic entities. The aeromagnetic discordance between the two appears to be related to a fault that offsets sequences of the same lithotectonic assemblage. Questions remain as to the age and kinematic significance of the aeromagnetically defined fault.

WABIGOON SUBPROVINCE

Onaman–Tashota Greenstone Belt

The Onaman–Tashota greenstone belt (Figures 13.1, 13.3) forms the central feature of eastern Wabigoon Subprovince. The main portion of this belt has been remapped in the past 5 years (Figure 13.3) and the results show a much greater volume of synvolcanic to late orogenic gabbroic intrusions than previously thought (e.g., Stott and Straub 1998). Current geochronological (D. Davis and others, Royal Ontario Museum), Nd isotopic, and geochemical work on widely distributed rock samples across this belt will be used to assist in subdividing the belt into several tectonostratigraphic assemblages. Some of these assemblages are, in a first order sense, apparent from significant differences in age of volcanism. Analysis of the chemistry and petrogenetic characterization of assemblages is currently in progress; some age determinations remain to be completed in areas where intermingling of assemblages is being resolved. The current geochronological record, including most recent U–Pb zircon age determinations (by Don Davis and colleagues at the Royal Ontario Museum) from various units in the Onaman–Tashota greenstone belt shows a more varied history of volcanism than once thought (*see* Figure 13.3). On the basis of field relationships, some of the ages from intrusions are interpreted to be inherited, reflecting older, underlying crust. A spectrum of Meso- to Neoarchean ages is represented in detrital zircon grains from sandstone units across the belt, including the southern margin of the English River Subprovince.

Chondrite-normalized rare earth element (REE) patterns for almost 200 samples of tholeiitic basalt across the width of this greenstone belt are mostly flat or with weakly depleted light REE, and slightly greater than 10× chondrite. Some units show a slight negative Eu anomaly. Trace element variation diagrams for basalt suggest a predominant juvenile, non-arc affinity with exceptions in the southern part of the belt underlying tuff sequences of the 2.74 Ga calc-alkaline volcanic centres and some strata in the vicinity of Willet Lake, east of Toronto Lake.

Built upon these assemblages of basalt are calc-alkaline felsic to intermediate volcanic centres that decrease in age southwards from the 2.739 Ga Marshall Lake assemblage through 2.734 to 2.722 Ga volcanic centres at Venus Lake and Metcalfe Lake, respectively, to a <2.707 Ga dacitic sequence on Humboldt Bay, Lake Nipigon. The latter might correspond episodically with <2.707 Ga metasedimentary strata above the Metcalfe Lake dacite and a 2.703 Ga dacitic sequence west of Lake Nipigon (Tomlinson et al. 1999; 2000) in the northern Obonga belt. The intermediate to felsic volcanic rocks across the Onaman–Tashota belt are typically strongly enriched in Th with a pronounced negative Nb anomaly. They show light REE enrichment and heavy REE depletion with little or no Eu anomaly, features that are typical of calc-alkaline arc magmatism. The presence of large, 2.735–2.740 Ga felsic volcanic centres on the north and south margins of the greenstone belt creates an apparent symmetry of crustal growth on the flanks of the belt. These broad centres contain synvolcanic plutons and accompanying hydrothermal alteration and the most notable base metal mineralization in the belt (e.g., Marshall Lake). Synorogenic alteration associated with gold mineralization is concentrated in 3 domains: the complexly faulted Beardmore–Geraldton greenstone belt, strained zones in the Metcalfe Lake felsic volcanic centre, and farther north in the Tashota Lake–Emily Lake road area.

A suite of 64 samples of volcanic and intrusive rocks across the greenstone belt has been analyzed for Nd isotopes. The felsic rocks (volcanic and plutonic) from throughout the region show predominant Nd model ages of 2.8 to 2.9 Ga, and initial epsilon Nd values of -0.1 to +1.5 (28 of 41 samples). Five samples from the north, at Marshall Lake, Toronto Lake, Girvan Lake, Tashota and the Esnagami tonalite, have Nd model ages in the 3.0 to 3.3 Ga range. Both the synvolcanic Onaman pluton at the centre of the belt and the late-tectonic Sollas pluton on the northern margin have Nd model ages of 2.9 to 3.0 Ga. Several other synvolcanic to late-tectonic plutons from throughout the region have Nd model ages of 2.8 to 2.7 Ga. The mafic rocks have initial epsilon Nd values of +1.0 to +4.0, with the majority between +2 and +3, indicating a lack of significantly older recycled crust. The exception is at Toronto Lake in the north, where lower epsilon Nd values are observed.

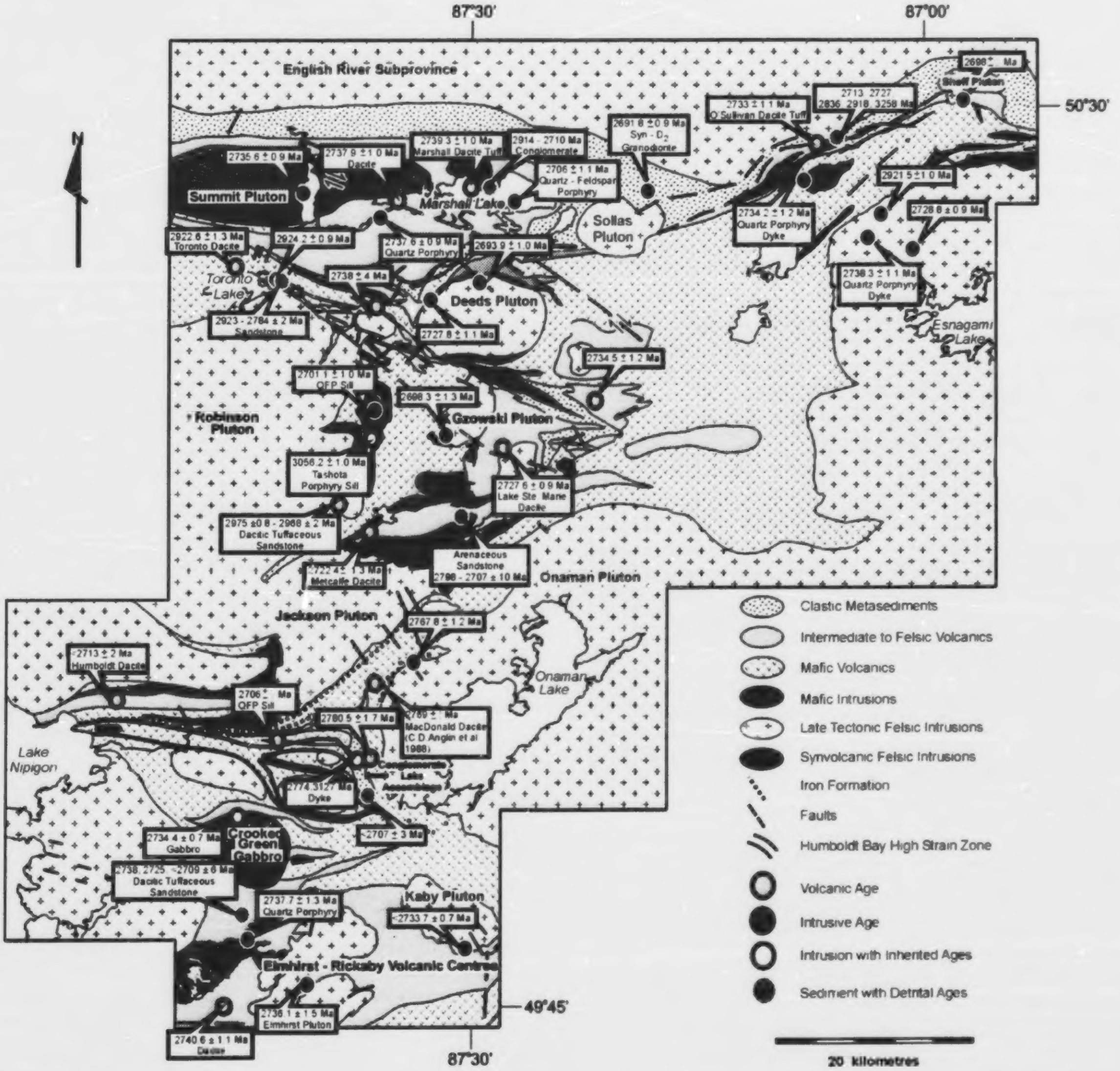
87°30'
87°00'
50°30'
49°45'
87°30'
N
English River Subprovince
2698 ± Ma
Shell Pluton
2713, 2727, 2836, 2918, 3258 Ma
2733 ± 1.1 Ma O'Sullivan Dacite Tuff
2691.8 ± 0.9 Ma Syn - D2 Granodiorite
2735.6 ± 0.9 Ma
2737.9 ± 1.0 Ma Dacite
2739.3 ± 1.0 Ma Marshall Dacite Tuff
2914 - 2710 Ma Conglomerate
2706 ± 1.1 Ma Quartz - Feldspar Porphyry
Summit Pluton
Marshall Lake
Sollas Pluton
2921.5 ± 1.0 Ma
2728.8 ± 0.9 Ma
2734.2 ± 1.2 Ma Quartz Porphyry Dyke
2922.6 ± 1.3 Ma Toronto Dacite
2924.2 ± 0.9 Ma
2737.6 ± 0.9 Ma Quartz Porphyry
2693.9 ± 1.0 Ma
2738.3 ± 1.1 Ma Quartz Porphyry Dyke
Toronto Lake
2738 ± 4 Ma
Deeds Pluton
2923 - 2784 ± 2 Ma Sandstone
2727.8 ± 1.1 Ma
Esnagami Lake
2734.5 ± 1.2 Ma
2701.1 ± 1.0 Ma QFP Sill
2698.3 ± 1.3 Ma
Robinson Pluton
Gzowski Pluton
3056.2 ± 1.0 Ma Tashota Porphyry Sill
2727.6 ± 0.9 Ma Lake Ste. Marie Dacite
2975 ±0.8 - 2968 ± 2 Ma Dacitic Tuffaceous Sandstone
Arenaceous Sandstone 2798 - 2707 ± 10 Ma
2722.4 ± 1.3 Ma Metcalfe Dacite
Onaman Pluton
Jackson Pluton
2767.8 ± 1.2 Ma
~2713 ± 2 Ma Humboldt Dacite
2706 ± Ma QFP Sill
Onaman Lake
2780.5 ± 1.7 Ma
2769 ± Ma MacDonald Dacite (C.D. Anglin et al. 1988)
Lake Nipigon
Conglomerate Lake Assemblage
2774, 3127 Ma Dyke
~2707 ± 3 Ma
2734.4 ± 0.7 Ma Gabbro
Crooked Green Gabbro
2738, 2725, ~2709 ± 6 Ma Dacitic Tuffaceous Sandstone
2737.7 ± 1.3 Ma Quartz Porphyry
Kaby Pluton
~2733.7 ± 0.7 Ma
Elmhirst - Rickaby Volcanic Centres
2736.1 ± 1.5 Ma Elmhirst Pluton
2740.6 ± 1.1 Ma Dacite
Clastic Metasediments
Intermediate to Felsic Volcanics
Mafic Volcanics
Mafic Intrusions
Late Tectonic Felsic Intrusions
Synvolcanic Felsic Intrusions
Iron Formation
Faults
Humboldt Bay High Strain Zone
Volcanic Age
Intrusive Age
Intrusion with Inherited Ages
Sediment with Detrital Ages
20 kilometres

Figure 13.3. Summary of geology and U–Pb age determinations in the central Onaman–Tashota greenstone belt.

Together, the isotopic data suggest several conclusions. Firstly, 2.74 to 2.72 Ga felsic volcanism cannibalized older felsic crust. Widespread evidence of recycled early Neoarchean to Mesoarchean crust is comparable to the complex pattern of crustal contamination noted by Tomlinson et al. (1999; 2000) in the central Wabigoon. Secondly, associated mafic volcanism was relatively juvenile. Thirdly, the basement in the northern half of the belt may contain a much older crustal component than is currently recognized at the surface. The oldest dated rock from this region, a porphyry sill, is 3.056 Ga, but three felsic volcanic rocks have significantly older Nd model ages of 3.28, 3.21 and 3.19 Ga.

The overall structural geometry of the belt has remarkably consistent northward dip. Bedding and parallel tectonic schistosity dip moderately to steeply north, similar to that in the Shebandowan greenstone belt in the Wawa Subprovince and the central part of the Uchi Subprovince. This regional structural observation across widely spaced greenstone belts may mirror the dominant north-dipping crustal reflectivity from Wawa to Uchi subprovinces, evident from the Western Superior Lithoprobe Transect (White et al. 1999). This structural character continues across the northern boundary of the Onaman–Tashota greenstone belt into the English River Subprovince. The northern margin of the Onaman–Tashota greenstone belt is affected by regional D_2 transpressive deformation. Northeast of Marshall Lake at the English River Subprovince boundary, a 2.692 Ga intrusion, possibly a phase of the Sollas pluton, is interpreted, from its internal structures and relation to surrounding metasedimentary rocks, to have intruded during the late stage of regional D_2 deformation. This deformation corresponds in style to that throughout the English River Subprovince (Stott and Corfu 1991; Corfu, Stott and Breaks 1995) and adjacent greenstone belts. It significantly predates a similar, transpressive deformation that affected the Quetico Subprovince and adjacent greenstone belts at 2.685–2.680 Ga (Corfu and Stott 1998).

South-Central Wabigoon Subprovince

A project aimed at defining the extent of Mesoarchean crustal precursors in the south-central Wabigoon Subprovince stems from recent mapping and isotopic studies that indicate scattered material of 3.4–3.0 Ga (Henry et al. 1998; Tomlinson et al. 1999; Percival et al. 1999; Tomlinson 2000) in this region. In the Shikag–Garden Lake area, tonalite, tonalite gneiss and anorthositic rocks generally have Nd model ages <2.9 Ga, whereas granodiorite and granite have model ages in excess of 3.0 Ga and in two locations, in excess of 3.3 Ga (Tomlinson and Percival 2000). Further to the west, biotite granite of the Indian Lake batholith (north of Ignace) has Nd model ages from two locations of 2.80 and 2.84 Ga, and older precursors are indicated in tonalite gneiss of the Hillyer Creek dome (2.95 Ga), felsic fragmental rocks of the Perch Lake belt (3.03 Ga), tonalite gneiss west of Mine Centre (2.98 Ga), tonalite gneiss northwest of Eltrut Lake (2.90 Ga), tonalite gneiss from the Valora area (2.91 Ga) and foliated tonalite south of Ignace (2.85 Ga) (Tomlinson and Percival 2000). A significantly older Nd model age of 3.26 Ga comes from a hornblende-biotite tonalite gneiss west of Raven Lake. Collectively, these data suggest that Mesoarchean crust in the southern Wabigoon Subprovince is not restricted to the Marmion batholith, Steep Rock and Lumby Lake greenstone belts, but appears to extend west, at least to Mine Centre in the southwest and Valora in the northwest, and northeast to the Obonga Lake – Garden Lake area. Model ages >3.34 Ga suggest the presence of crust of Winnipeg River vintage beneath some parts of the central Wabigoon (Tomlinson and Percival 2000). U–Pb geochronology will further constrain the age and extent of crustal precursors.

Mapping of the Petry River area of the south-central Wabigoon Subprovince focussed on establishing regional controls on gold, platinum group element and rare-metal mineralization as well as examining the origin and relationships between Mesoarchean and Neoarchean rocks. Within this area, narrow Archean greenstone belts were recognized that are cut by several varieties of foliated to gneissic plutonic rocks and massive granite batholiths. The greenstone belts comprise metabasalt with rare gabbro, sedimentary units and a single komatiite locality. A platform sequence, represented by a 30 m-thick section of quartz arenite, separates metabasalt from biotite tonalite in an area 25 km northwest of Graham, Ontario. The platform sequence and komatiite provide geologic evidence that volcano-plutonic sequences of the Petry River area form an extension of the Mesoarchean domain in the Atikokan–Lumby Lake area.

Regional mapping traced the Marmion fault 100 km northeast from Atikokan to Selwyn Lake. Splays of the fault are mineralized with gold in the Atikokan area and dikes of peraluminous granite are broadly associated with the fault at Selwyn Lake. The peraluminous granite dikes, some of which contain visible molybdenite, are a possible bedrock source for anomalous concentrations of Li, Mo, Th, U, REEs, Y and Nb in lake-bottom sediment in the Selwyn–Wawang lakes area. A mafic intrusive complex of Archean gabbro and Proterozoic diabase occurs at Little Trewartha Lake and a hornblendite stock is present south of Weaver Lake. These intrusions are recommended as exploration targets for platinum group elements.

SACHIGO SUBPROVINCE

Blackbear, Yelling and Stull Lake Areas

Mapping (1995–2000) of a 12 000 km^2 area along the Ontario–Manitoba border (*see* Figure 13.1) is providing new geological maps and an assessment of the mineral potential and regional tectonic evolution. The east-southeasterly trending Ponask–Sachigo, Stull, Ellard and Yelling greenstone belts are separated by plutonic domains and the broad Stull–Wunnummin, South Kenyon and North Kenyon fault zones. Work in the current season at Blackbear Lake marked the completion of regional mapping in the southeast corner of the area. Eastern extensions of the Stull and Ellard greenstone belts as well as the Stull–Wunnummin and South Kenyon faults were traced through this area. Transects along the Stull, Wapikani and Yelling rivers identified western extensions of major batholiths, greenstone slivers and the Kenyon faults. The largest greenstone belt in the area, at Stull Lake, consists of four structural panels (Stone and Pufahl 1995), and has been re-examined in detail in the last two seasons. New mapping, sampling and geochronology have focussed on defining positions of major faults in the belt, examining its poorly exposed western extremities, distinguishing alkaline and calc-alkaline volcanic sequences, and studying the relationships between various sedimentary and volcanic packages.

Preliminary isotopic and geochronologic studies indicate that the area is divisible into an early Neoarchean to Mesoarchean domain south of the Stull–Wunnummin fault, a Neoarchean domain between the Stull–Wunnummin and Kenyon faults and a Paleoarchean domain north of the Kenyon fault (Skulski et al., 1999). These domains possibly represent crustal blocks that were tectonically accreted during growth of the Superior Province and whose boundaries have been subsequently reactivated as faults. A lack of regional data inhibits extrapolation of these domains across the northern Superior Province or correlation with other tectonic domains in the south.

The northern Superior area has potential for a wide variety of mineral commodities including rare metals, platinum-group metals, base metals, gold, diamonds and carving stone. Numerous gold occurrences associated with regionally extensive faults indicate high potential for discovering economic deposits of gold. Anomalous numbers of kimberlite indicator grains in modern alluvium suggest that the area is worthy of exploration for diamonds.

Knee Lake – Gods Lake Area

Integrated studies of the Knee Lake belt (cf. Corkery et al. 1999) continued in the northeastern Gods Lake area in 2000 (*see* Figure 13.1). Two distinct sequences of Hayes River Group metavolcanic rocks with opposing facing directions are separated by a northeast trending dextral fault. In addition to its transcurrent component, north-side-up dip-slip motion on the fault carries amphibolite-facies rocks on the northwest over greenschist-facies units to the southeast. Geochronological studies on units of the Oxford Lake Group to the southwest show that the volcanic subgroup has a depositional age of 2.720 Ga, whereas the sedimentary subgroup has a broad range of detrital zircon ages ranging from 3.647 to 2.711 Ga. Possible sources of ancient *ca.* 3.6 Ga zircon grains occur in fault-bounded blocks along the northern margins of the northern Superior Province. Geochronological data from the Knee Lake area date Hayes River volcanism at 2.83 Ga, and SHRIMP data on detrital zircon grains indicate that turbiditic sandstone are synvolcanic and volcanic-derived. Folding of the Hayes River Group predates deposition of coarsening-upwards clastic sediments and iron formation, the former containing 2.937–2.822 Ga detrital zircon grains. The Oxford Lake volcanic subgroup was extruded at 2.722 Ga in southern Knee Lake and was followed by deposition of fluvial-clastic, sedimentary subgroup sandstone with detrital zircon grains ranging from 2.798 to 2.707 Ga.

A unique feature of Gods Lake is that it provides access to the granitoid terrane separating the Munro Lake and Knee Lake greenstone belts. This well exposed section of gneiss complexes and plutons was mapped and sampled for geochemistry in a cooperative MGS–GSC program. As well as contributing to the Knee Lake greenstone belt mapping project, this section will provide geochemical, isotopic and geochronological information to a regional transect focussing on the age and history of plutonic and gneissic terranes across the northwestern Superior Province.

Assean Lake Area

The Assean Lake block at the northwestern margin of the Superior Province represents a collage of east-southeast-trending Archean crustal segments that are overprinted by northeast-trending zones of Late Archean and Early Proterozoic deformation and metamorphism. The Assean Lake block can be subdivided into three lithotectonic domains. In the south, a migmatitic supracrustal rocks include quartz arenite, arkose, and metagreywacke, with some amphibolite and silicate-facies iron formation. A central panel is dominated by tonalitic orthogneiss which cuts the northern package consisting of mafic to intermediate metavolcanic rocks and migmatitic greywacke.

Combined Sm–Nd isotopic and U–Pb zircon (TIMS and SHRIMP) results indicate that the Assean Lake block preserves Paleo- to Mesoarchean crust that underwent a complex and prolonged history spanning more than two billion years. These integrated mapping and isotopic studies across the northwestern Superior Province margin have resulted in a reinterpretation of the location and nature of the boundary zone between Archean rocks of the Superior Province and Paleoproterozoic rocks of the Trans-Hudson Orogen in the region northeast of Thompson.

NORTHERN TRANSECT

The poorly exposed northern Superior superterrane (Skulski et al. 2000) was mapped and sampled for geochemical, tracer isotopic and geochronological studies in a transect from Kistigan Lake to northeast of Red Cross Lake. Major geological domains sampled include the northern Sachigo subprovince and Pikwitonei gneiss complex. The northwest-trending north Kenyon fault is a kilometre-scale mylonite zone; narrower mylonite zones of similar trend characterize the south Kenyon fault.

DISCUSSION

Elucidation of the tectonic history of the Uchi subprovince remains key to understanding the relationship between the North Caribou and adjacent terranes. There exists widespread, yet cryptic evidence of an early, non-penetrative deformation event (pre-D_1) across the southern margin of the North Caribou craton, in the Pickle Lake (pre-2.860 Ga), Confederation Lake (*ca.* 2.85 Ga), and Red Lake (2.894–2.750 Ga) greenstone belts. The first penetrative deformation event (D_1) recorded in this region may have been diachronous from pre-2.74 Ga in the Pickle Lake area, to between 2.733 and 2.724 Ga in the Confederation Lake area, to between 2.742 and 2.718 Ga in the Red Lake belt. The timing of subsequent D_2 deformation, interpreted to be related to collision between the North Caribou and Winnipeg River cratons (Uchian phase of the Kenoran orogeny) appears best constrained in the Red Lake belt at *ca.* 2.718 Ga. Diachroneity may also characterize this event, as units as young as 2.713 Ga were affected in the St. Joseph assemblage to the west.

The southwest part of the Uchi Subprovince (Rice Lake–Lake Winnipeg greenstone belts) shows little evidence of affinity with the North Caribou margin prior to 2.72 Ga, and records a younger tectonic history that involves tectonic juxtaposition of units after 2.704 Ga, the age of posttectonic plutons in the Red Lake and Confederation Lake greenstone belts. Post-2.704 Ga events may be related to deformation that affected the English River Subprovince (cf Corfu et al. 1995). Together, these observations show that the southern margin of the North Caribou terrane had an extended history of magmatism and deformation, perhaps reflecting transient conditions at a long-standing Andean margin.

Within the Uchi Subprovince, evidence for the presence of crustal fragments which are exotic to the North Caribou margin is limited. Candidates include the Pickle Crow assemblage, with evidence of pre-2.86 Ga deformation, which would have been accreted prior to 2.745 Ga. Geochemical, isotopic and geochronological studies are underway to test this hypothesis. The *ca.* 2.85 Ga Trout Bay assemblage in the Red Lake greenstone belt may represent a juvenile oceanic terrane that faces toward older strata built on the North Caribou margin and was juxtaposed prior to 2.75 Ga. The undated Black Island assemblage in the Lake Winnipeg area has ocean floor and arc geochemical signatures, faces toward a continental margin sequence, and is separated from it by D_1 shear zones formed after 2.704 Ga.

Along the northern margin of the North Caribou terrane, slivers of juvenile crust are bound by major, late, strike-slip shear zones. Ongoing mapping, in concert with geochronology and isotopic tracer studies, is unraveling the complex interaction between the North Caribou terrane and Northern Superior superterrane.

Ongoing work in the central and eastern Wabigoon regions is defining the age and extent of Mesoarchean crustal blocks and their relationships to Neoarchean sequences. At least two discrete Mesoarchean sources are present: 1) a northern, >3.34 Ga terrane with probable affinity to the Winnipeg River Subprovince, known from ancient detrital zircon grains in Mesoarchean platform sequences and old Nd model ages in Neoarchean granites; and 2) a southern *ca.* 3 Ga block, exposed in the Marmion batholith and environs. Whether the two Mesoarchean blocks were assembled during *ca.* 2.7 Ga tectonism, which also juxtaposed juvenile Neoarchean rocks of the western Wabigoon, or carry an older common history, is an avenue of current research. Integrating the tectonic and magmatic history with crustal profiles derived from Lithoprobe seismic data represents a unique challenge and opportunity.

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14. Project Units 98-006 and 98-007. Precambrian Features Under the James Bay and Hudson Bay Lowlands

G.M. Stott[1] and B.J. Berdusco[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Large parts of the Superior Province underlie the Phanerozoic cover of both the James Bay and Hudson Bay Lowlands. To date, this, plus the poor bedrock exposure in the eastern and northernmost exposed Uchi–Sachigo superterrane (Figure 14.1), has permitted only limited success in correlating the components of this superterrane with parts of the Superior Province in northwestern Quebec. A joint Ontario Geological Survey – Geological Survey of Canada project is planned to distinguish various geological features (greenstone belts, iron formation units, metasedimentary domains, etc.) and correlate regional-scale Archean domains or superterranes under the Phanerozoic cover. Regional Geophysics staff of the GSC will be reprocessing the Ontario Department of Mines/Geological Survey of Canada aeromagnetic data of the 1960s, covering the region mainly north of Latitude 51°. Recent exploration for diamond-bearing kimberlite in the Hudson Bay Lowlands (see Sage 1997) has provided new evidence of Archean inliers in the eastern Hudson Bay Lowlands plus borehole samples of underlying Precambrian crust that will help establish a correspondence between rock types and magnetic intensity.

This summary outlines some of the Precambrian features that we have tentatively interpreted to underlie the lowland-cover and which will be enhanced when the reprocessing is completed. These features include generalized boundaries between Archean greenstone-granite and metasedimentary terranes (subprovinces). Economic implications from this regional interpretation are also summarized.

Figure 14.1 displays geological features and major tectonic subdivisions for exposed Archean crust in northwestern Ontario from the Bedrock Geology map of Ontario; for Precambrian crust underlying the adjoining Hudson Bay Lowlands and James Bay Lowlands, the shaded relief image of total magnetic field intensity is shown. The contrasts in magnetic susceptibility on local scales between different rock types and contrasts in magnetic intensity between regional domains permit us to interpret, as a first approximation, major lithological and tectonic subdivisions. As a way of highlighting features to be distinguished in this project, we have outlined some of the domains of low magnetic intensity, under the northern and eastern Hudson Bay Lowlands, within which are typically found greenstone belts. We have also interpreted boundaries between major Archean domains that appear to correspond to terranes and superterranes of exposed Archean crust in northwestern Ontario and in western Quebec. The following are brief comments and interpretations about some of the broader Precambrian features underlying the lowlands.

EASTWARD EXTENSION OF THE PIKWITONEI-GODS LAKE DOMAIN

The region of broad, high magnetic intensity and pronounced structural grain under the northern Hudson Bay Lowlands is similar to and on strike with that of the Pikwitonei granulite domain, Split Lake

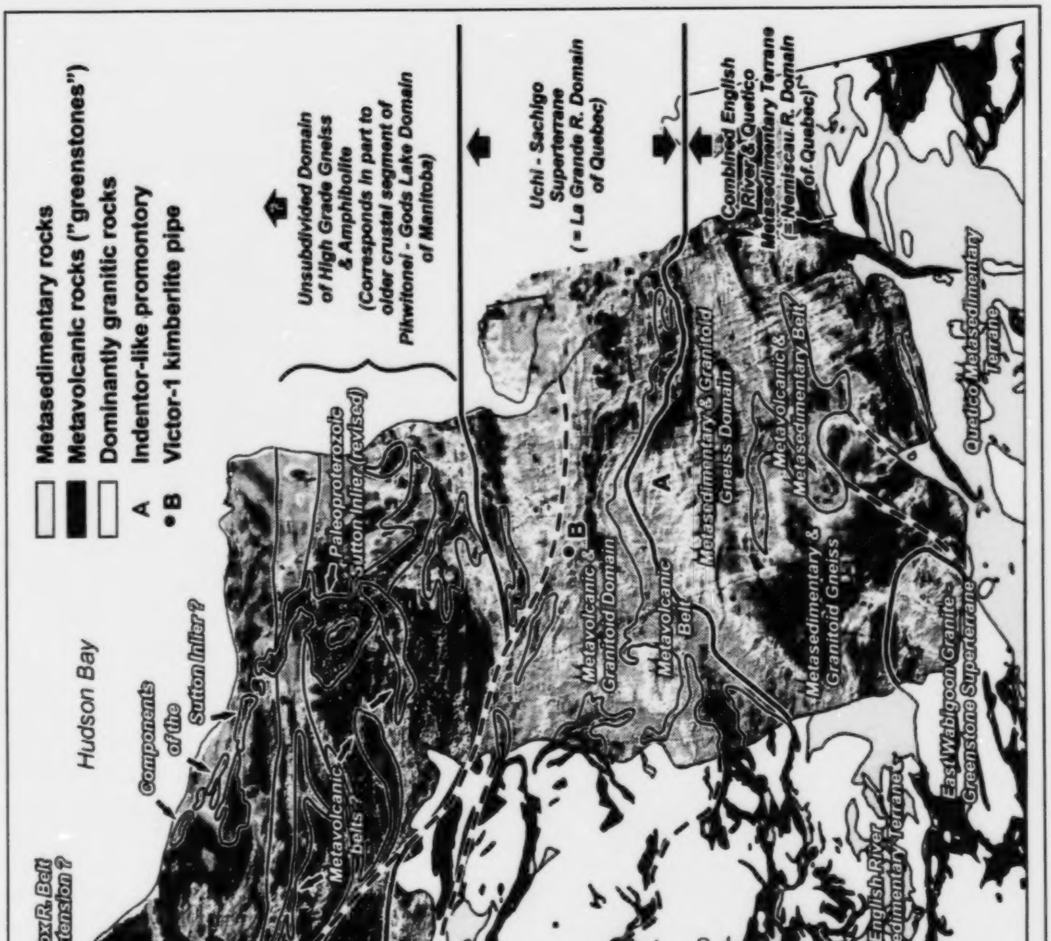
Metasedimentary rocks
Metavolcanic rocks ("greenstones")
Dominantly granitic rocks
A Indentor-like promontory
•B Victor-1 kimberlite pipe
Hudson Bay
Components of the Sutton Inlier ?
Fox R. Belt extension ?
Paleoproterozoic Fox R. belt
Winisk R. Fault
Paleoproterozoic Sutton Inlier (revised)
Metavolcanic belts ?
Unsubdivided Domain of High Grade Gneiss & Amphibolite (Corresponds in part to older crustal segment of Pikwitonei - Gods Lake Domain of Manitoba)
Uchi - Sachigo Superterrane (= La Grande R. Domain of Quebec)
Combined English River & Quetico Metasedimentary Terrane (= Nemiscau R. Domain of Quebec)
Metavolcanic & Granitoid Domain
Metavolcanic Belt
Metasedimentary & Granitoid Gneiss Domain
Metavolcanic & Metasedimentary Belt
Metasedimentary & Granitoid Gneiss
Quetico Metasedimentary Terrane
East Wabigoon Granite-Greenstone Superterrane
English River Metasedimentary Terrane
Uchi - Sachigo Superterrane
A
B
Older Crustal Component on Strike with Gods Lake Domain (Manitoba)
On Strike with Pikwitonei Domain (Manitoba)
North & South Kenyon Faults
Stull-Wunnumin Fault Zone
N
100 kilometres

Figure 14.1. Precambrian features and subdivisions interpreted to underlie the James Bay and Hudson Bay lowlands.

block and the northern part of the Gods Lake domain in Manitoba. These granitoid gneiss and greenstone domains in Manitoba contain a broad range of Archean ages including pre-3.8 Ga crust (e.g. Böhm et al. 2000). The eastward extension of these plutonic domains in Ontario is on strike with, and is interpreted to be contiguous with, a portion of the Bienville domain in Quebec.

SUTTON INLIER

The Paleoproterozoic Sutton Inlier in the Hudson Bay Lowlands, just south of Hudson Bay, is surrounded by Phanerozoic sedimentary rocks, and comprises shallowly north- and east-dipping strata of continental margin-type rocks—dolomite, argillite, chert and iron formation–overlain by diabase sills. The Sutton Inlier is a segment of the Trans-Hudson Orogen, which wraps around the western and northern margins of the exposed Superior Province from Manitoba to the Cape Smith Belt in northern Quebec. The inlier is connected to a set of narrow, sinuously folded, supracrustal remnants that extend northward to the south shore of Hudson Bay. Elements of the Trans-Hudson Orogen are exposed in parts of Manitoba and the Hudson Bay Lowlands. Re-interpretation of the magnetic intensity patterns that characterize this region suggests several points to consider.

The Proterozoic Fox River Belt of Manitoba does not appear to continue eastwards across the northern Hudson Bay Lowlands (cf. Thurston and MacFadyen 1992). It probably continues north to Hudson Bay near the Manitoba–Ontario border and links to the Internides of the main Trans-Hudson Orogen linear gravity anomaly just offshore from Ontario. Strata from the Trans-Hudson Orogen offshore in Hudson Bay seem to reappear as folded units (linear magnetic anomalies) north of the Sutton Inlier and trend southwards discontinuously towards the inlier. These features need further discrimination to establish their affinity and extent.

The Sutton Inlier has for many years been treated as a single, continuous package of rock as currently portrayed on geological maps (*after* H. Bostock 1970). An examination of the aeromagnetic patterns in its vicinity suggests the Sutton Inlier is not a single large domain but a set of southwestward-convex-shaped inliers strung along a line. They resemble "klippe-like" features comprising shallow water platform sedimentary deposits including iron formation, and gabbroic sills that might have been transported southwards onto the Archean craton from the main Trans-Hudson Orogen belt in Hudson Bay. Strata are also aeromagnetically apparent to the north and east of the currently defined Sutton Inlier. The stratigraphic units compare closely in lithologic sequence with the Nastapoka Formation on the eastern shore of Hudson Bay (Chandler and Parrish 1989) and part of the Povungnituk Group of Cape Smith Belt in northern Quebec.

EASTWARD EXTENSION OF UCHI–SACHIGO SUPERTERRANE

The Sachigo and Uchi subprovinces of northwestern Ontario are interpreted to form an Archean superterrane that appears to converge under the eastern Hudson Bay Lowlands. It lies on strike with the La Grande River granite-greenstone domain of Quebec. The superterrane lies north of a major indenter-like promontory under the eastern Hudson Bay Lowlands. This feature, like other "indenters" in northwestern Ontario (e.g., at Savant Lake, Shebandowan and Manitouwadge), closes northwards and borders a "bow-tie" aeromagnetic pattern on its north flank, which appears to reflect shortening and exhumation of deeper gneissic crust. The domain forming this indenter-like feature is interpreted to comprise granitoid and metasedimentary gneissic rock, corresponding to the English River terrane.

EASTWARD EXTENSION OF ENGLISH RIVER AND QUETICO METASEDIMENTARY TERRANES

Beneath the James Bay Lowlands, there is a strong likelihood that the English River and Quetico metasedimentary subprovinces converge and that the Wabigoon Subprovince pinches out eastwards. Discrimination of this has important tectonic implications for the original nature of these subprovinces. East of the Wabigoon granite-greenstone subprovince, a narrow zone of discontinuous volcanic rocks and iron formation appear to mark the sharp magnetic intensity contrast between the (higher grade?) English River terrane to the north and the Quetico metasedimentary terrane to the south. We suggest that the converging English River and Quetico terranes, which contain narrow remnants of volcanic arcs such as the Melchett Lake belt northeast of Lake Nipigon, resemble telescoped inter-arc basins that wrap around the east end of a Wabigoon microcontinent and continue on strike with the Nemiscau River metasedimentary domain in Quebec. The merged English River – Quetico terrane might be a telescoped analogue to modern interarc basins such as the Solomon and Coral sea basins north and south of east Papua-New Guinea (e.g. Busby and Ingersoll 1995), which serves as a conceptual modern analogue for the eastern Wabigoon Subprovince.

ECONOMIC IMPLICATIONS

Some additional insight should develop from this study on the regional structures and the tectonic framework of Archean terranes in the northernmost parts of Ontario. From this will develop a better understanding of the distribution of gold deposits, rare metal pegmatite occurrences, PGE- and base metal-bearing gabbro bodies, and structural controls on localising diamondiferous kimberlite pipes.

The Uchi–Sachigo superterrane contains several, very long, continuous, southeast-trending fault zones that trace the curviplanar contacts between greenstone belts and adjacent granitoid batholiths (Osmani and Stott 1988). Some of these might yet be identified as significant tectonic interfaces, owing in part to the presence of rare metal pegmatite bodies and gabbro intrusions along these fault zones. Some of these faults likely continue under the eastern Hudson Bay and James Bay lowlands. Those, such as the Stull–Wunnummin fault zone (Figure 14 1), which are known to contain significant gold prospects, might be traceable to the northeast trending boundary inferred here to separate the Uchi–Sachigo superterrane and the English River terrane. This northeast trending boundary, flanking the indentor-like promontory (A on Figure 14.1) might also be a faulted contact similar to the left-handed transcurrent Miniss River fault near Sioux Lookout. Another example is the South Kenyon fault zone, a splay of which might be related to the Sachigo River gold occurrence in the Ellard Lake greenstone belt (Stone et al. 1998).

The intersection of major fault zones, such as the Winisk River Fault, and regional linear uplifts, such as the Henrietta Maria arch have been postulated to localize kimberlite magmatism (e.g. Card et al. 1997) including several pipes in the vicinity of the Victor-1 pipe (B on Figure 14.1).

The presence of rare metal pegmatite bodies along Archean terrane boundaries suggests that such intrusions should occur under the James Bay Lowlands along the eastward continuation of the eastern Wabigoon-English River terrane boundary and the Uchi–English River boundary.

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15. Project Unit 95-15. Geology of the Blackbear, Yelling and Stull Lake Areas, Northern Superior Province, Ontario

D. Stone[1] **and J. Hallé**[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Geology Department, Lakehead University

INTRODUCTION

Field activities in 2000 marked the completion of a regional mapping survey that has been ongoing at the north side of the Superior Province of Ontario since 1995. The study area of approximately 12 000 km^2 (Figure 15.1) represents a transect of Superior Province geology extending 120 km northward from Sachigo Lake, Ontario adjacent to the Manitoba border.

Goals of the northern Superior Project are broadly to provide a new set of geologic maps and to unravel the complex tectonic history of the area in relation to better exposed and more extensively studied parts of the southern Superior Province. Toward these objectives, two or three 1:50 000 scale maps have been published annually. Sampling for lithogeochemistry, thermobarometry and isotopic and geochronologic studies (e.g., Skulski et al. 1999) has been done concurrent with mapping and further samples were taken for geochronology this season by staff of the Royal Ontario Museum. The economic potential of the area has been the focus of systematic mapping and sampling of bedrock and surficial materials. For example, sheared and greenschist-altered rocks associated with regional faults in the area have been routinely assayed for gold. Till and modern alluvium are processed for indicator minerals of kimberlite, metamorphosed massive sulphide deposits and gold (e.g., Stone, Hallé and Lange 2000).

Bedrock mapping and sampling has been integrated with work by geologists of the Manitoba Industry, Trade and Mines (e.g., Fedikow et al. 1998) with the goal of providing maps and databases that are comparable across the Ontario–Manitoba border. The work is part of the Western Superior NATMAP of the Geological Survey of Canada (see Percival et al. this volume).

Fieldwork for the current season was done in three areas. Work at Blackbear Lake represents the completion of regional mapping and sampling in the southeast corner of the study area (Figure 15.1). The Yelling Lake area was briefly reexamined with staff of Manitoba Industry, Trade and Mines to further resolve the geology and position of regional faults in poorly exposed areas near the Manitoba-Ontario border. Stull Lake represents the largest and best-exposed greenstone sequence in the northern Superior area and was mapped at the onset of the project. Stull Lake geology and mineral potential have been reexamined in detail over the past two field seasons. Results of current work in the three sub-areas as well as a brief overview of the regional geology are presented here.

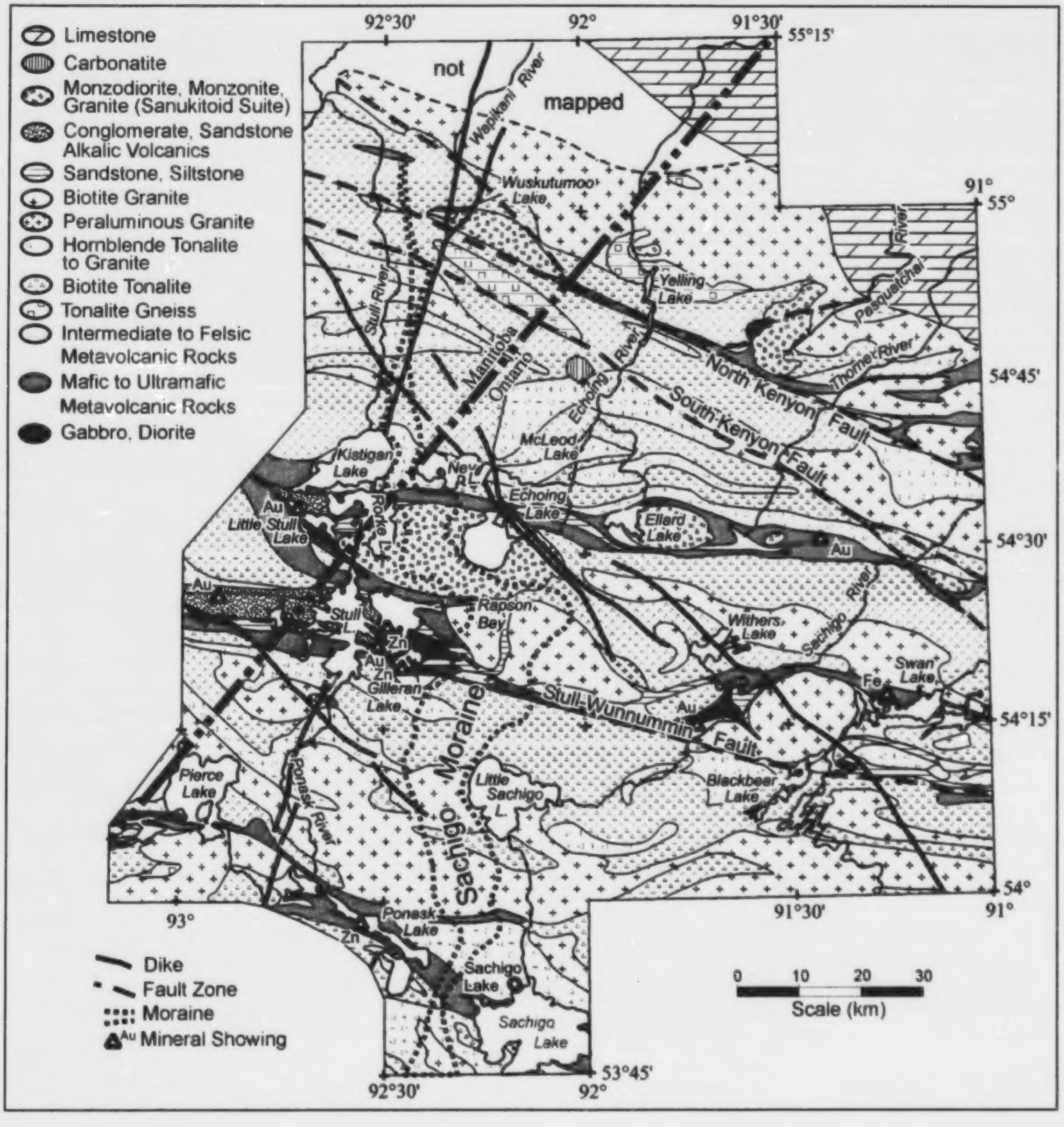

Figure 15.1. Geology of the northern Superior area.

GEOLOGY

Blackbear Lake Area

The Blackbear Lake area is centered approximately 50 km northeast of the community of Sachigo Lake and was mapped previously by Bennett and Riley (1969).

The geology of the Blackbear Lake area is characterized by thin, variably tapered and bifurcated anastomosing greenstone belts interspersed with felsic plutonic rocks. The greenstone belts represent eastern extensions of major greenstone sequences at Ellard Lake and Stull Lake (Figure 15.1). Mafic metavolcanic rocks occur primarily in the eastern Ellard greenstone belt (north side of Figure 15.2) and in the area from Tamblyn through Stables to Swan lakes. For the most part, these appear to represent pillowed submarine flows of basaltic composition although a combination of high strain and metamorphism has stretched and disrupted pillows and transformed the flows to amphibole gneisses at many localities. Coarse, variably massive to strongly foliated gabbro occurs in large intrusions southwest of Tamblyn Lake and east of Blackbear Lake and as small bodies at scattered localities in mafic flows.

Clastic metasedimentary rocks comprise interbedded fine sandstone and siltstone at Meston, Tamblyn and Swan lakes and in greenstone slivers south of Swan Lake. A small unit of arkosic sandstone composed of rounded quartz and feldspar grains characteristic of Timiskaming-type sequences occurs southwest of Meston Lake (Figure 15.2). Cherty, pyritic zones, located principally in the Swan Lake area, are probably representative of thin metamorphosed iron formations within volcanic strata.

Intermediate to felsic metavolcanic rocks occur widely at Swan Lake where the greenstone belt attains a maximum width of 7 km. These comprise variably stretched heterolithic to monolithic volcanic fragmental rocks and associated quartz and feldspar porphyritic subvolcanic intrusions. In the eastern Swan Lake area, felsic tuffs are interbedded with clastic metasediments and cherty, possibly flow-banded rhyolite is observed.

Greenstone sequences in the Blackbear Lake area typically are metamorphosed to amphibolite facies and show an assemblage of amphibole+feldspar±epidote and the development of amphibole porphyroblasts. Sandy metasedimentary rocks have an assemblage of biotite+feldspar±garnet. Where strongly sheared by faults such as the Stull–Wunnummin fault, mafic volcanic sequences appear to have been retrograded to an assemblage of greenschist minerals such as chlorite+feldspar+quartz±carbonate.

Felsic plutonic rocks underlie more than 80% of the Blackbear Lake area and occur as broad batholithic belts and as oval to elongate plutons within greenstone sequences. Biotite tonalite to granodiorite (biotite tonalite suite) occurs widely and is typically a white to grey, medium-grained and foliated to gneissic rock composed of essentially plagioclase, quartz and up to 10% biotite.

On a regional scale (Figure 15.2) the biotite tonalite suite is interlayered with the biotite granite suite, which is characterized by massive, pink leucocratic biotite granodiorite to granite. Biotite granite also occurs as distinct late oval plutons such as south of Stables Lake. Coarse, mesocratic foliated hornblende tonalite to granodiorite of the hornblende suite occurs at scattered localities and locally shows development of blocky potassium-feldspar megacrysts. Although widespread on a regional scale (*see* Figure 15.1), characteristically late oval monzodioritic to granitic plutons of the sanukitoid suite are not observed at Blackbear Lake. A poorly exposed body of coarse white biotite+muscovite granite (peraluminous suite) occurs in association with metasedimentary rocks west of Meston Lake.

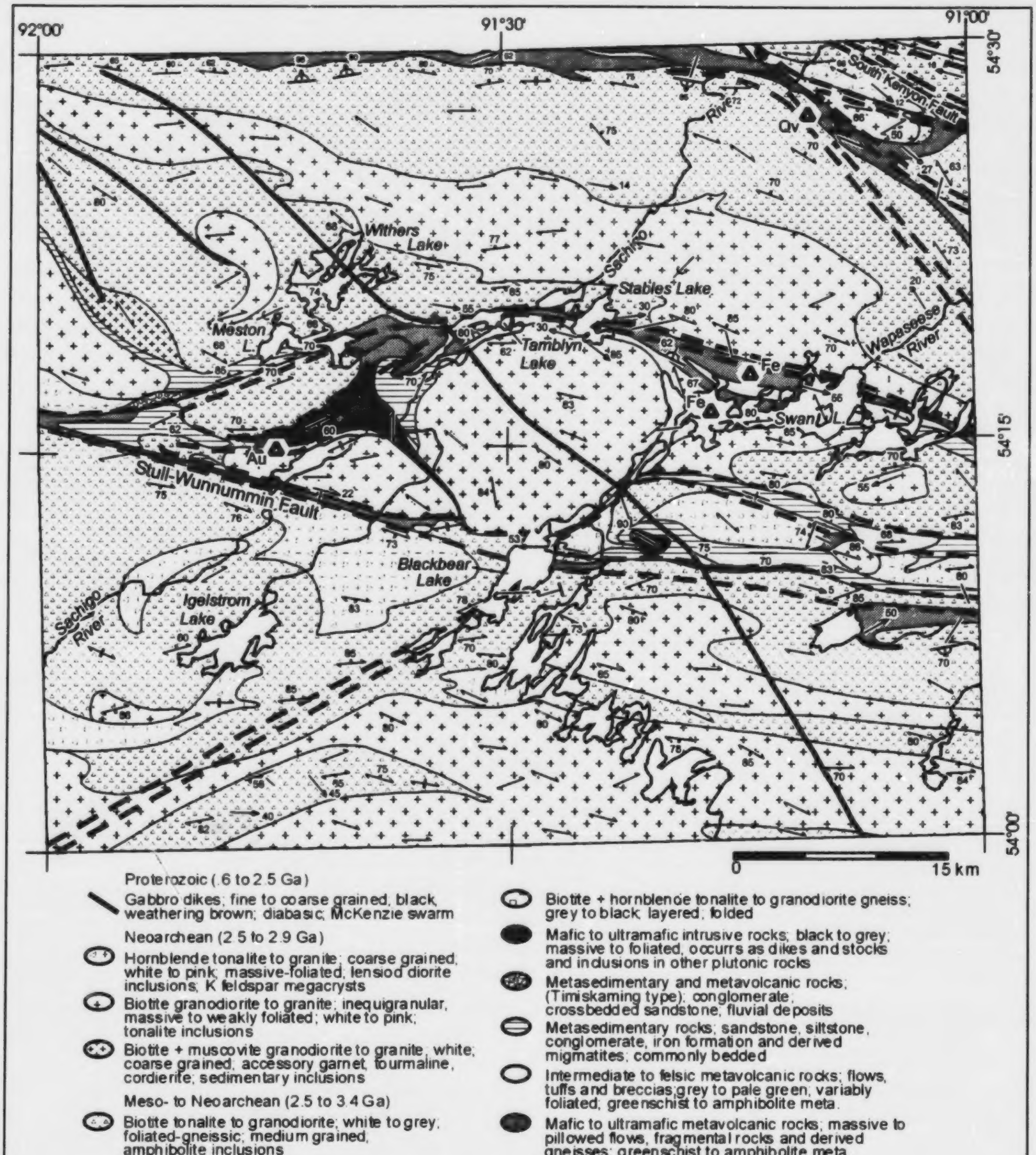
92°00'
91°30'
91°00'
54°30'
54°15'
54°00'
South Kenyon Fault
Qv
River
Sachigo
Withers Lake
Stables Lake
Meston L.
Tamblyn Lake
Wapaseese River
Fe
Swan L.
Au
Stull-Wunnummin Fault
Blackbear Lake
Igelstrom Lake
Sachigo River
0
15 km
Proterozoic (1.6 to 2.5 Ga)
Gabbro dikes; fine to coarse grained, black, weathering brown; diabasic; McKenzie swarm
Neoarchean (2.5 to 2.9 Ga)
Hornblende tonalite to granite; coarse grained, white to pink; massive-foliated; lensiod diorite inclusions; K feldspar megacrysts
Biotite granodiorite to granite; inequigranular, massive to weakly foliated; white to pink; tonalite inclusions
Biotite + muscovite granodiorite to granite, white; coarse grained; accessory garnet, tourmaline, cordierite; sedimentary inclusions
Meso- to Neoarchean (2.5 to 3.4 Ga)
Biotite tonalite to granodiorite; white to grey; foliated-gneissic; medium grained, amphibolite inclusions
Biotite + hornblende tonalite to granodiorite gneiss; grey to black; layered; folded
Mafic to ultramafic intrusive rocks; black to grey; massive to foliated, occurrs as dikes and stocks and inclusions in other plutonic rocks
Metasedimentary and metavolcanic rocks; (Timiskaming type); conglomerate, crossbedded sandstone; fluvial deposits
Metasedimentary rocks; sandstone, siltstone, conglomerate, iron formation and derived migmatites; commonly bedded
Intermediate to felsic metavolcanic rocks; flows, tuffs and breccias; grey to pale green; variably foliated; greenschist to amphibolite meta.
Mafic to ultramafic metavolcanic rocks; massive to pillowed flows, fragmental rocks and derived gneisses; greenschist to amphibolite meta.
Foliation; dip unknown, inclined, vertical
Gneissosity; inclined
Inclined pillow; top unknown, top known
Bedding with top unknown; inclined
Mineral lineation with plunge
Z-style fold
Glacial striation
Geologic contact; inferred
Fault, fault zone
Mineral showing

Figure 15.2. Geology of the Blackbear Lake area.

The Blackbear Lake area is transected by east-southeasterly trending regional faults including the Stull–Wunnummin and South Kenyon. These structures are characterized by broad (1 to 2 km wide) zones of mylonitic and schistose plutonic and supracrustal rocks and are bifurcated into splay faults. For example, splays of the Stull–Wunnummin fault curve easterly through Meston, Tamblyn and Stables lakes and are preferentially localized in supracrustal rocks. A northeast-trending fault merges with the Stull–Wunnummin fault at Blackbear Lake (Figure 15.2).

Archean supracrustal and plutonic rocks as well as mylonite zones are cut by northwest-trending dikes of coarse, massive, brown weathered diabase. The dikes are tentatively correlated with the 1.3 Ga MacKenzie swarm.

Yelling Lake Area

Bedrock in the area of the Manitoba–Ontario border west of the Echoing River between McLeod and Yelling lakes (Figure 15.1) is extensively blanketed by glacial ice-margin deposits associated with the Sachigo moraine with the result that the geology had been poorly defined by regional mapping in this area (Stone and Hallé 1997). A few days of additional helicopter supported mapping was done in the present season jointly with staff of Manitoba Industry, Trade and Mines to improve the level of geologic information for the area. The work consisted primarily of traverses along the Stull, Wapikani and Yelling rivers that provide reasonably complete, north-trending sections of exposed bedrock.

The Stull River transect identified a series of biotite tonalite, hornblende tonalite and biotite granite bodies and small greenstone slivers characterized by an overall east-southeast structural fabric. On the basis of aeromagnetic interpretation (ODM–GSC 1967) several plutonic bodies can be tentatively correlated over distances of 30 km between the Stull and Yelling rivers. Mylonite zones possibly representing western extensions of the North Kenyon and South Kenyon faults are identified in the Stull and Wapikani River transects. The North Kenyon fault appears to splay in the area of the Manitoba–Ontario border with branches extending westward to the north and south of Wuskutumoo Lake (Figure 15.1). The South Kenyon fault remains parallel to and about 10 km south of the North Kenyon fault in the area of the Manitoba–Ontario border. Traverses along the Echoing River north of Yelling Lake have identified complex enclaves of tonalite gneisses and greenstone remnants within the large granite batholith in that area. The source of a distinct southeasterly-elongated aeromagnetic anomaly in the area between Wuskutumoo Lake and the Manitoba–Ontario border remains unresolved. Plutonic rocks appear to occur in this area based on aerial inspection. Possibly the anomaly represents a sanukitoid pluton or mafic intrusion mantled by metasedimentary rocks containing iron formation.

Stull Lake Area

On the basis of initial mapping, the Stull Lake greenstone belt was divided into four structural panels transected by major faults (see Figure 12.1 of Stone and Pufahl, 1995). Panels 1 and 4 are dominated by mafic metavolcanic flows and deep-water sediments and were interpreted to belong to the ca 2830 Ma Hayes River Group. Panels 3 and 2 of coarse clastic sedimentary rocks and felsic volcanic rocks were assigned to the ca 2709 Ma sedimentary subgroup of the Oxford Lake Group and to an unnamed volcanic group, respectively (*see* Syme et al. 1997 and Corkery and Skulski, 1998 for descriptions of the Hayes River and Oxford Lake groups in Manitoba).

The initial mapping raised exciting questions about the geology and mineral potential of the Stull Lake area with the result that further detailed work including sampling for geochemistry and geochronology was done in recent years including the present season. 1) Geochemical sampling showed that panel 2 is divisible into alkaline and calc-alkaline components. Combined mapping, geochemistry and geochronology are being used to resolve the extent and relations between the two types of volcanic rocks. 2) Regional mapping indicates that the Stull Lake greenstone belt is cut by two major splays of the Stull-Wunnummin fault (Figure 15.1). Detailed mapping has been focused on the identification of these structures as well as subsidiary faults within the belt. 3) It is unclear to what extent fine grained and typically deformed clastic metasedimentary rocks, which occur at several panel boundaries, belong to the Hayes River or Oxford Lake groups. Detailed mapping and sampling for geochronology has been done to address this question. 4) Western extensions of the Stull Lake greenstone belt are poorly known due to lack of exposure. Further mapping in conjunction with staff of Manitoba Industry, Trade and Mines as well as compilation of geologic and geophysical maps generously donated by Wolfden Resources Ltd are being used to upgrade the geologic maps in this area.

ECONOMIC GEOLOGY

Previous mineral exploration in the Blackbear Lake area consists of sporadic drilling by Sherritt Gordon Mines Limited in the 1970s. Exploration targets appear to have been mainly geophysical anomalies associated with sedimentary units in greenstone slivers at Blackbear, Tamblyn and Swan lakes and along the Stull–Wunnummin fault. Drill core logs described iron sulphide mineralization at these localities.

During the present survey, several gossan zones were identified in metavolcanic rocks at Swan Lake (Figure 15.2). These comprise pyrite and pyrrhotite associated with chert and probably represent metamorphosed iron formation horizons within metavolcanic rocks. The gabbro intrusions located east of Blackbear Lake and south of Tamblyn Lake are potential sources of Cu-Ni sulphide and PGE mineralization. Samples taken in 1999 from the triangular gabbro body south of Tamblyn Lake produced negligible PGE values, however further samples were taken in this season from the gabbros as well as from the gossan zones at Swan Lake; assays are in progress.

The most attractive assay result from the 1999 survey has come from a 1 m wide zone of sheared granite south of Meston Lake (Figure 15.2). The shear zone contains quartz veins and disseminated molybdenite and up to 1170 ppb Au. The assayed shear zone is one of a network of faults that represent splays of the Stull–Wunnummin fault. The mineralization alludes to potential for gold through a broad area affected by the faults from Meston through Tamblyn and Stables to Swan lakes. Parts of the eastern Ellard Lake greenstone belt are also strongly deformed by splays of the South Kenyon fault and have potential for gold mineralization. For example, a quartz mass of 60 m extent was identified at the faulted margin of the Ellard greenstone belt (*see* NE corner of Figure 15.2) and has been sampled for gold analysis.

The economic potential of the Yelling Lake area is difficult to assess due to poor exposure. Dikes of peraluminous granite within sheared tonalite suggest possible rare metal mineralization west of Wuskutumoo Lake. Major faults and associated splays raise the possibility of shear-zone hosted gold mineralization. The aeromagnetic anomaly southeast of Wuskutumoo Lake needs to be evaluated for potential mafic intrusive rocks hosting Cu-Ni sulphides and PGE mineralization.

In 2000, Wolfden Resources Inc drilled for gold on properties with significant proven reserves at Little Stull Lake and Twin Lakes west of Stull Lake (Richardson et al. 1996; Figure 15.1). Regional mapping indicates that the gold mineralization at these properties is associated with splays of the Stull–Wunnummin fault. Further mapping in the previous two seasons has aided in defining mineralized extensions of these faults in the Stull Lake area. For example, sheared sediments at several localities such as on the east side of Stull Lake have yielded up to several hundred parts per billion Au (Figure 15.1). An assay of 1061 ppb Au came from an arsenopyrite-bearing quartz vein at the margin of a fault.

Two base-metal occurrences have been examined at Stull Lake. A previously trenched occurrence at the entrance to Rapson Bay (Figure 15.2) consists of small, scattered gossan zones within felsic volcanic rocks at the shoreline. These are mineralized with disseminated sulphides and locally remobilized coarse massive sulphides including pyrrhotite, pyrite, sphalerite, chalcopyrite and galena. Assays of 1.4% Zn and smaller amounts of Pb and Cu and trace amounts of Au and Ag have been obtained from the showing. A second showing at Gilleran Lake consists of disseminated sphalerite in an assemblage of clinozoisite and chlorite with garnet and staurolite probably representative of altered basalt. The Gilleran showing has produced assays of over 0.5% Zn.

Initial sampling identified anomalous numbers of kimberlite indicator grains in beach sands of the Stull Lake area (Stone, Morris and Crabtree, 1999). In recent years, more sampling and processing of modern alluvium and till has been done to further define anomalous zones. Bulk samples have been obtained from anomalous beach deposits to extract larger numbers of indicator grains for analysis.

REGIONAL OVERVIEW

Results of new mapping at Blackbear, Yelling and Stull lakes augments the work of previous seasons and provides new insight on the geology, mineral potential and structure of a remote and underexplored part of the Canadian Shield. On the one hand, the work in the Northern Superior area provides a basis for, 1) comparisons of Archean geology between the north and south Superior Province and, 2) resolving the tectonic evolution and, 3) evaluating mineral potential of the area. On the opposite hand, the work raises new questions on the correlation of gross tectonic architecture of this area with other parts of the Superior Province where the geology is either better known or else largely unknown.

Firstly, by way of comparison at a regional scale, the northern area shows suites of supracrustal and plutonic rocks comparable to those found in other parts of the Superior Province. For example, greenstone belts can be subdivided into the tectonic assemblages of Thurston and Chivers (1990), which are representative of most Archean greenstone belts. Six major suites of plutonic rocks including the biotite tonalite, tonalite gneiss, hornblende tonalite, biotite granite, peraluminous granite and sanukitoid suites are recognized in the northern Superior area. These are characteristic of the range of plutonic rocks that occur broadly in the western Superior Province (e.g., Stone 1998). Further, metamorphism is typically upper greenschist to amphibolite facies with no evidence of having achieved granulite grade.

The uniqueness of northern Superior geology may be inherent in structural characteristics such as greenstone belts that are more narrow and elongate and typically more highly strained than those in the south. The northern Superior area is transected by three broad mylonite zones of regional extent (Osmani and Stott 1988) and numerous subsidiary splays. These features allude to higher levels of late, dominantly transpressional strain in the north than is represented in the southern Superior Province.

Secondly, preliminary isotopic and geochronologic studies (Skulski et al. 1999) indicate three distinct and probably fault-bounded crustal blocks in the northern Superior area. These include a 2.8 to 2.9 Ga block south of the Stull–Wunnummin fault, a 2.7 Ga block between the Stull–Wunnummin and Kenyon faults and a pre-3.4 Ga block north of the Kenyon structures. The blocks potentially represent a series of terranes that were amalgamated by accretionary tectonism during growth of the Superior Province although details such as the precise location of block boundaries and the timing of their amalgamation need to be addressed through further age dating and petrotectonic studies.

Problems arise in consideration of the regional extent of crustal blocks beyond margins of the northern Superior area. For example, the North Caribou terrane of Thurston et al. (1991) is a large Mesoarchean crustal block represented by the pre-2.95 Ga North Sandy and Keewaywin assemblages at Sandy Lake, 100 km south of the present area. It is unclear however whether the early Neoarchean to Mesoarchean block in the south part of the present area is an extension of the North Caribou terrane or a separate tectonic element of the Superior Province. Major boundary faults can be traced for hundreds of kilometres west-northwest and east-southeast of the northern Superior area (e.g., Osmani and Stott 1988) and imply that the intervening crustal blocks may also be regionally extensive and belt-like in shape much like subprovinces in the south. The Paleoarchean block in the northern part of the present area may represent an extension of the pre-3.4 Ga Split Lake Block (Heaman et al. 1999) 300 km northwesterly at the Superior Province margin. Further work is required in northern Manitoba to establish this linkage however. Likewise, further work is needed through a broad area including Big Trout Lake, Kasabonika and Webequie in search of fundamental crustal subdivisions in the northeastern Superior Province of Ontario.

Thirdly, the northern Superior area has potential for a wide variety of mineral commodities including rare metals, platinum-group metals, base metals, gold, diamonds and carving stone. Among these, the potential for discovering economic deposits of gold is favourable in view of numerous known occurrences and the association of the precious metal with broad shear zones, which are extensive in the area. Anomalous numbers of kimberlite indicator grains in modern alluvium suggest that the area is worthy of exploration for diamonds.

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16. Project Unit 95-14. Geology of the Petry River Area, South-Central Wabigoon Subprovince

D. Stone[1] and J. Hallé[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Lakehead University, Thunder Bay

INTRODUCTION

The south-central Wabigoon Subprovince holds a wide range of mineral resources. These include historic iron mines, gold associated with regional faults, base metals in altered volcanic sequences, platinum group elements in mafic intrusions and rare metal pegmatites. The area is also interesting because it contains fragments of Mesoarchean (pre-2.9 Ga) crust as well as Neoarchean rocks whose ages fall mainly in the range of 2.75 to 2.7 Ga. For example, a Mesoarchean domain is represented by the tonalite batholith at Marmion Lake and greenstone belts stretching from Steep Rock through Finlayson to Lumby lakes (Davis and Jackson, 1988; Figure 16.1), however the northeastern extent of this domain is not well known.

Geologic mapping at a scale of 1:50 000 was initiated in 1995 on parts of the south-central Wabigoon Subprovince centered in the Atikokan–Ignace area (Figure 16.1). The work is focussed on examining regional controls on mineralization and providing a geologic framework for studies on the origin and relationship between Mesoarchean and Neoarchean rocks. Mapping by the Ontario Geological Survey is integrated with the Western Superior NATMAP of the Geological Survey of Canada and the Western Superior LITHOPROBE transect. Collectively, these projects address the regional tectonic framework of the western Superior Province (*see* for example, Percival et al. this volume; Tomlinson et al. 1998). In the current season, sampling for geochronology was done in the south central Wabigoon Subprovince and regional mapping was extended northeasterly into the Petry River area (see Figure 16.1). This report summarizes the main observations on the geology, structure and mineral potential that result from the current season's work.

GEOLOGY

The Petry River area is situated 150 km northwest of Thunder Bay, Ontario and includes the towns of English River and Graham. The area is accessible by Highway 17 and a network of logging roads.

The Petry River area was mapped previously by Sage et al. (1974a, b) and is underlain by narrow Archean greenstone belts, several varieties of foliated to gneissic plutonic rocks and voluminous massive granite intrusions. Greenstone belts are up to a few kilometres wide and have complex, highly curved and branching forms in the English River–Graham area (Figure 16.2). These appear to represent distal extensions of the Lumby Lake belt (Jackson 1985), which occurs at the southwest corner of the present area. The greenstone belts are composed for the most part of metabasalt that locally show pillow textures but are largely transformed to amphibole gneiss by pervasive high levels of strain and thermal metamorphism. Kilometre-scale slivers and inclusions of amphibole gneiss also occur in plutonic rocks such as north of Wawang and Pakashkan lakes.

Coarse, massive to foliated gabbro is interspersed with metabasalt and constitutes a minor component of greenstone belts; the largest gabbro body occurs at Little Trewartha Lake (Figure 16.2). An outcrop of komatiite (31% MgO) is identified within mafic flows 5 km northeast of Savoy Lake. Metasedimentary rocks comprising greywacke and cherty variably magnetiferous to pyritic iron formation occur at scattered localities.

Brown weathered, variably laminated to thinly bedded gritty quartz arenite is exposed discontinuously over a distance of about 5 km along the banks of the English River northeast of Savoy Lake (Figure 16.2). These metasedimentary rocks, which contain local lenses of conglomerate with tonalite clasts, are typically a few tens of metres thick and separate foliated biotite tonalite to the west from amphibole gneiss to the east. The quartz arenite and contiguous metavolcanic rocks probably represent a platform sequence overlying tonalite basement to the west although development of a pervasive foliation prevents clear identification of an unconformity at the base of the sedimentary rocks. Unlike the Steep Rock Group 70 km to the southwest (Wilks and Nisbett, 1988), carbonate and iron formation members were not identified in the platform sequence at this locality. Ultramafic volcanic rocks which characteristically occur in upper parts of platform sequences (Thurston and Chivers 1990) are rare at this locality and are represented by one outcrop of komatiite in mafic gneiss east of the quartz arenite.

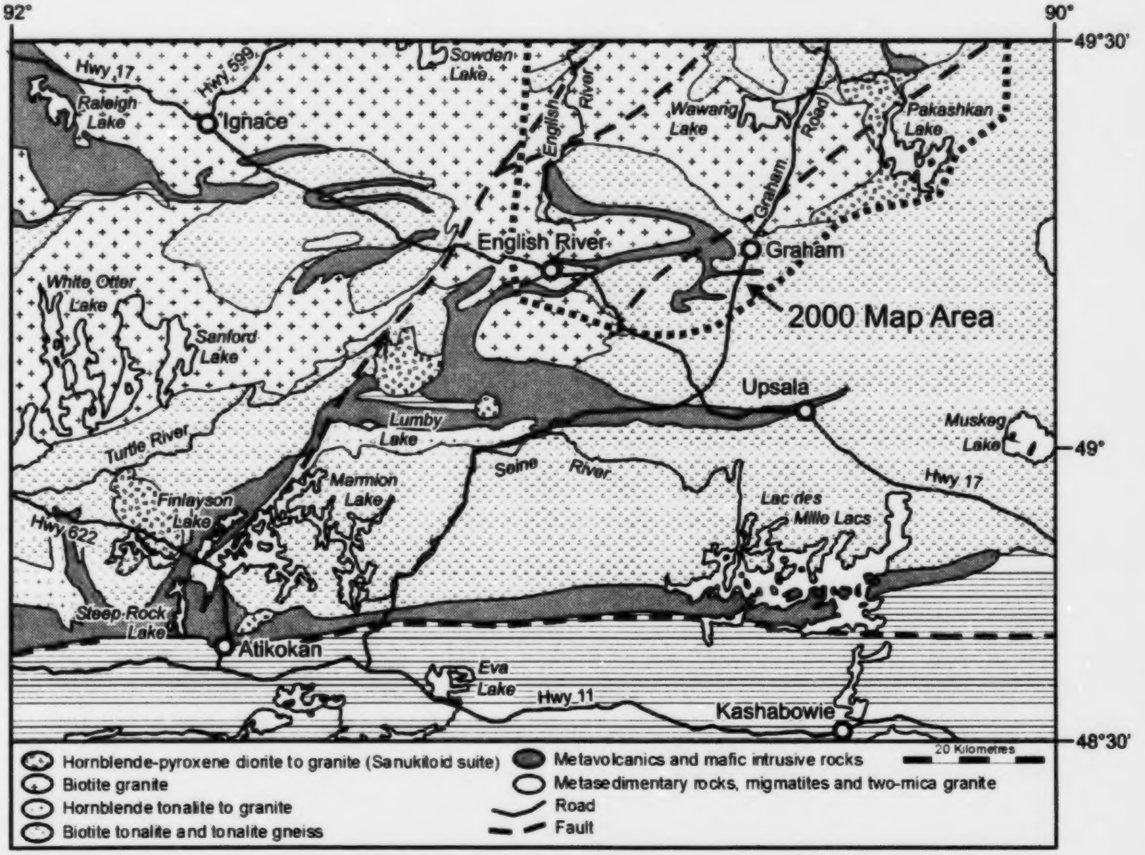

Figure 16.1. Geology of the south-central Wabigoon Subprovince.

Felsic plutonic rocks underlie 90% of the Petry River area and are divisible into 6 major suites. Biotite tonalite to granodiorite (biotite tonalite suite) occurs widely and is commonly associated with greenstone slivers such as at the English River locality discussed above. Biotite tonalite, which is typically a coarse grained and grey to white leucocratic rock, ranges texturally from massive through weakly to strongly foliated varieties and also grades texturally to tonalite gneiss. Gneiss are composed of two or more interlayered varieties of leucocratic and mesocratic biotite tonalite and may contain amphibolite layers. Rocks of the gneissic suite occur in small irregular units at scattered localities (Figure 16.2).

The hornblende tonalite, peraluminous granite and sanukitoid suites are minor components of the Petry River area. Hornblende tonalite is a coarse, granular and foliated leucocratic to mesocratic rock that grades compositionally to granite through progressive development of potassium-feldspar megacrysts. Rocks of the hornblende suite show variable intensity of foliation development and occur as irregular units interlayered on a gross scale with biotite tonalite. The peraluminous suite is represented by coarse,

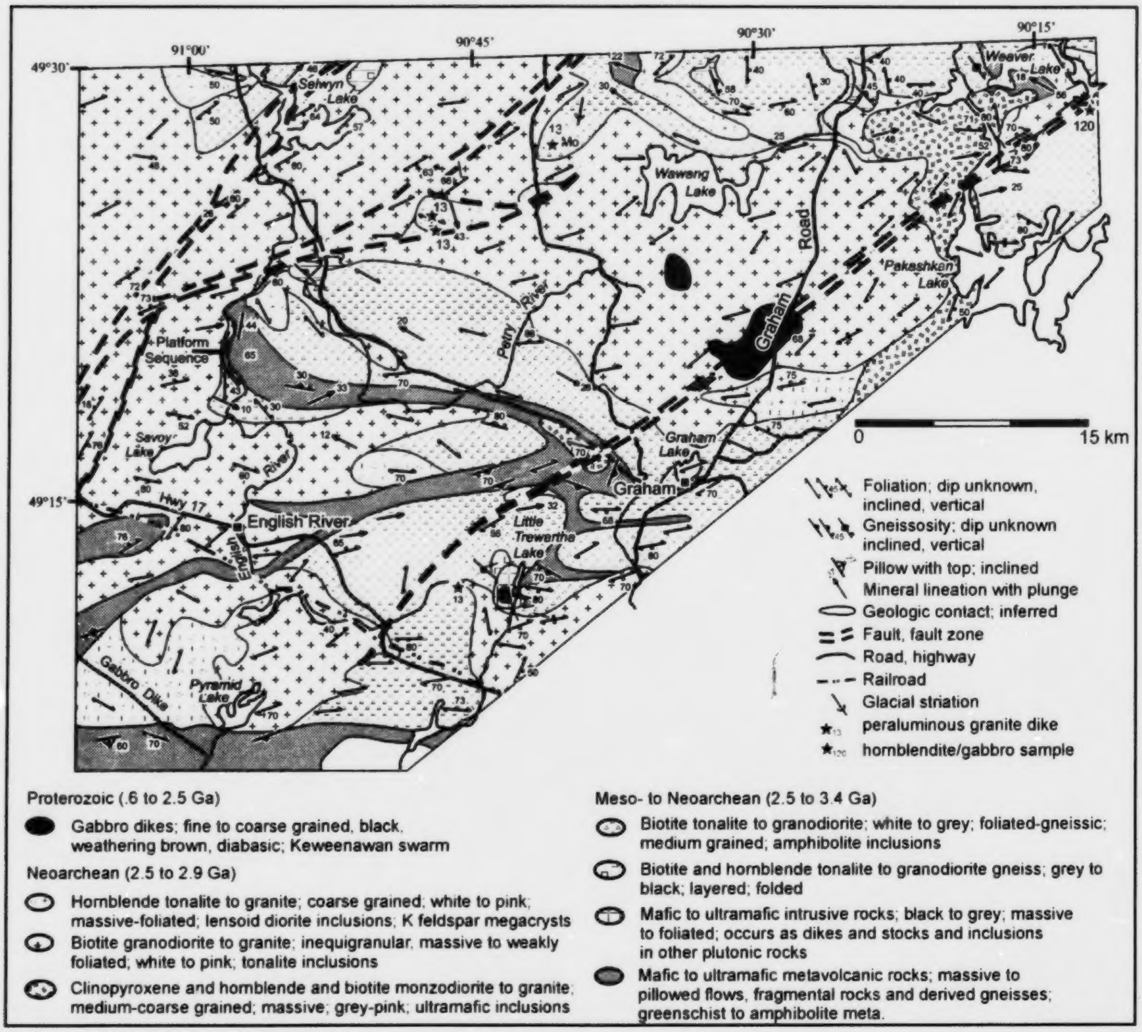
91°00'
90°45'
90°30'
90°15'
49°30'
49°15'
Selwyn Lake
Weaver Lake
Wawang Lake
Mo
Platform Sequence
Petry River
Graham Road
Graham Lake
Pakashkan Lake
Savoy Lake
Hwy 17
English River
English River
Graham
Little Trewartha Lake
Pyramid Lake
Gabbro Dike
120
0
15 km
Foliation; dip unknown, inclined, vertical
Gneissosity; dip unknown inclined, vertical
Pillow with top; inclined
Mineral lineation with plunge
Geologic contact; inferred
Fault, fault zone
Road, highway
Railroad
Glacial striation
peraluminous granite dike
hornblendite/gabbro sample
Proterozoic (.6 to 2.5 Ga)
Gabbro dikes; fine to coarse grained, black, weathering brown, diabasic; Keweenawan swarm
Neoarchean (2.5 to 2.9 Ga)
Hornblende tonalite to granite; coarse grained; white to pink; massive-foliated; lensoid diorite inclusions; K feldspar megacrysts
Biotite granodiorite to granite; inequigranular, massive to weakly foliated; white to pink; tonalite inclusions
Clinopyroxene and hornblende and biotite monzodiorite to granite; medium-coarse grained; massive; grey-pink; ultramafic inclusions
Meso- to Neoarchean (2.5 to 3.4 Ga)
Biotite tonalite to granodiorite; white to grey; foliated-gneissic; medium grained; amphibolite inclusions
Biotite and hornblende tonalite to granodiorite gneiss; grey to black; layered; folded
Mafic to ultramafic intrusive rocks; black to grey; massive to foliated; occurs as dikes and stocks and inclusions in other plutonic rocks
Mafic to ultramafic metavolcanic rocks; massive to pillowed flows, fragmental rocks and derived gneisses; greenschist to amphibolite meta.

Figure 16.2. Geology of the Petry River area.

white biotite-muscovite granite containing accessory garnet, tourmaline and apatite and molybdenite at one locality. Dikes of peraluminous granite occur between Selwyn and Wawang Lake and west of Little Trewartha Lake (Figure 16.2). Intrusions of the sanukitoid suite are recognized at Pakashkan Lake and west of Graham Lake. These intrusions are composed of coarse, fairly massive pink rock ranging compositionally from monzodiorite through quartz monzonite to granite.

Massive, pink leucocratic biotite granite is the most common rock in the Petry River area and occurs in forms ranging from veins and dikes through oval plutons to lobate batholiths. The majority of granite in the present area comprises parts of the Cecil Lake batholith that extends more than 100 km westerly to Ignace (Figure 16.1). Crosscutting relations suggest that the biotite granite suite and the sanukitoid suite are the youngest major Archean plutonic suites. These are cut by dikes and sills of coarse, massive brown-weathered diabase probably correlative with late Proterozoic Keeweenawan magmatism.

Archean rocks of the Petry River area are cut by two major northeasterly trending faults characterized by broad protomylonite zones. The Marmion fault (Stone et al. 1992) extends 100 km northeasterly from Atikokan and divides into two major splays that pass through Selwyn Lake and south of Selwyn Lake (Figure 16.2). The Selwyn Lake splay probably represents a continuation of the Brightsand Deformation Zone mapped 30 to 80 km northeast of the present area by Percival et al. (1999).

The second fault cuts and has possibly caused dextral offset of the sanukitoid pluton at Pakashkan Lake and is of unknown northeasterly extent.

ECONOMIC GEOLOGY

A high density lake sediment geochemical survey (Dyer and Breaks 1996) identified several anomalous areas where lake bottom sediments are enriched in rare-earth elements (REEs), Ba, Co, Cr, Fe, Mo, Nb, Sc, Sn, Th, U, V, Y and Zn. Broadly, the anomalous lakes overlie segments of the southern splay of the Marmion fault in the area between Selwyn and Wawang lakes and parts of the margins of the greenstone belt west of Graham (Figure 16.2). Although hindered by poor exposure, the present survey identified peraluminous granite dikes, one of which contains visible molybdenite, in the area between Selywn and Wawang lakes. These occurrences suggest that the area corresponding with the southern splay of the Marmion fault and the Axe Lake–McCausland River, Little Petry River and Mettawi Lake anomalies of Dyer and Breaks (1996) are prospective for rare-element pegmatite and molybdenite pegmatite.

The Rush Creek anomaly (Cr, Ba, Hf, Ti, Ta, Nb and Rb) and Oscar-Beach River anomaly (REEs, Y, V and Sc) of Dyer and Breaks (1996) correspond with poorly exposed segments of the greenstone belt west-northwest of Graham and bedrock mapping in this area has not provided any new information on possible sources of the anomalies. The Little Trewartha Lake anomaly of Dyer and Breaks (1996) is characterized by lake bottom sediments containing anomalous Cr, Fe and Co in addition to REEs, Y, V and Sc. This anomaly corresponds with a mafic intrusive complex of Archean gabbro and Proterozoic diabase (Figure 16.2), which may account for the high concentrations of Fe and transition metals. A peraluminous granite pegmatite dike was also mapped a few kilometres west of Little Trewartha Lake.

Several anomalies visible in aeromagnetic maps (ODM–GSC 1965) were investigated during bedrock mapping. For example, an anomaly 5 km north-northwest of Wawang Lake corresponds with a greenstone sliver where boulders of rusty pyritic iron formation were observed. Possibly, the aeromagnetic anomaly is caused by unexposed iron formation in the greenstone sliver. Likewise, an anomaly between northern Pakashkan Lake and Weaver Lake corresponds with an irregular metavolcanic enclave containing cherty sedimentary horizons probably representative of metamorphosed iron formation. In contrast, an aeromagnetic anomaly at Little Trewartha Lake lies within the mapped trace of a mafic intrusive complex of Archean gabbro and Proterozoic diabase associated with amphibole gneisses. The aeromagnetic anomaly also coincides with a lake bottom sediment anomaly of Dyer and Breaks (1996) discussed above. Although grab samples of the gabbro and diabase produced negligible PGE values, the Little Trewartha Lake area is none-the-less worthy of further exploration for base metals, rare metals and PGE metals.

Rusty boulders in the ditch of the Graham road east of Wawang Lake are mineralized with pyrite and minor chalcopyrite in quartz and have produced assays of up to 0.1% Cu. The source of the boulders is unknown. The most attractive assay result has come from a mafic intrusion within biotite tonalite south of Weaver Lake (Figure 16.2) and produced 200 ppb combined Au, Pt and Pd. The assayed rock is a coarse hornblendite with no visible sulphides. The mafic intrusion lies at the eastern margin of the mapped area and is of unknown but probably limited extent.

SUMMARY AND DISCUSSION

Regional mapping has provided an updated geologic map of the Petry River area and has identified several potential exploration targets as well as giving a frame of reference for interpretation of anomalies in lake-bottom sediment surveys. For example, the mafic intrusions at Little Trewartha and south of Weaver lakes are recommended as exploration targets for PGE mineralization. Likewise, the sanukitoid intrusions located 5 km west of Graham and at Pakashkan Lake are also candidate hosts for economic concentrations of platinum group elements by analogy with the PGE-mineralized sanukitoid intrusion at Entwine Lake, 150 km west in the south-central Wabigoon Subprovince (Stone 2000).

Dyer and Breaks (1996) interpreted anomalous concentrations of Li, Mo, Th, U, REEs and high field strength elements including Y and Nb in lake bottom sediments as an indication of rare element pegmatites and molybdenite pegmatites at three localities broadly in the area between Selwyn and Wawang lakes. The present survey provides support for this interpretation through the identification of three peraluminous granite dikes, one of which contains visible molybdenite in this area. Further, mafic intrusive rocks and a peraluminous granite dike are found in the area of Little Trewartha Lake where Dyer and Breaks (1996) noted lake bottom sediments enriched in transition elements and REEs. In summary, the bedrock mapping confirms the importance of lake-bottom sediment surveys as exploration guides for pegmatites and mafic intrusions, particularly in poorly exposed areas.

Platform sequences such as at the English River locality are characteristically associated with early Neoarchean to Mesoarchean greenstone sequences in the western Superior Province (Thurston and Chivers 1990). This, in addition to apparent continuity of greenstone belts from the Petry River area to Lumby Lake are an indication that Mesoarchean greenstone sequences of the Steep Rock–Lumby Lake area extend at least as far as Graham (Figure 16.1). The boundary of the Mesoarchean domain is undefined but is possibly marked to the north by the Marmion fault in the Selwyn-Wawang Lakes area. Peraluminous granite dikes suggest that parental sedimentary rocks were once present in the vicinity of the fault. Possibly the Marmion fault is superimposed on an earlier basin or continental margin structure, which contained sediments and represented the margin of a Mesoarchean crustal block.

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17. Project Unit 00-08. Geology of the Heaven Lake Greenstone Belt, Central Wabigoon Subprovince

T.R. Hart[1] and C.A. MacDonald[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Mapping of the Heaven Lake greenstone belt (Figure 17.1) evaluated 1) the economic potential of the belt in combination with the Ontario Treasure Hunt (OTH) Garden–Obonga geophysical survey (OGS 2000), and 2) the position of the belt within the tectonostratigraphic framework of the central Wabigoon subprovince as proposed by the Western Superior NATMAP project. This project characterized the metavolcanic and intrusive rocks of the Heaven Lake belt and their relationship to mineralization. Past exploration has concentrated on the gold and volcanogenic massive sulphide (VMS) potential associated with intermediate metavolanic rocks of the belt. Contrasting ages for two intermediate metavolcanic units indicate the existence of a tectonic boundary in the belt. A komatiite-carbonate-iron formation sequence has been correlated with a similar sequence in the Lumby Lake belt. The younger-age metavolcanic rocks could correlate with rocks of the Elmhirst–Rickaby volcanic centres.

The Heaven Lake greenstone belt is located approximately 100 km north of Thunder Bay and west of Lake Nipigon. Previous mapping by Milne (1964), Sage et al. (1974), Sage (1998), and Thurston, Cortis, and Chivers (1987) was at a reconnaissance scale. Lithogeochemistry, radiometric ages and Nd isotopic data are available from recent sampling by Tomlinson (in press) and Tomlinson et al. (1998). Recorded exploration began in about 1965 with the building of the Spruce River Road/Highway 527 and resulted in drilling of scattered diamond drill holes possibly following up electromagnetic anomalies, and prospecting for gold.

GENERAL GEOLOGY

The belt is dominated by the older Whitton assemblage with limited exposure of the younger Whistle assemblage. The Whitton assemblage is dominated by mafic metavolcanic rocks with minor interbedded intermediate tuffs and interflow chert-magnetite metasedimentary rocks isoclinally folded about an east-trending axis. The top of the assemblage contains a sequence of ultramafic flow, basalt flow, chert-magnetite banded iron formation, intermediate metavolcanic rocks, carbonate chemical metasedimentary rock capped by intermediate metavolcanic rock. The Whistle assemblage is restricted to the eastern edge of the belt, and consists of intermediate metavolcanic rocks and a granodiorite and gabbro-intruding basalts of the Whitton assemblage. Felsic plutonic rocks intrude the supracrustal rocks. Sibley Group metasedimentary rocks underlie discontinuous diabase sills of the Proterozoic Nipigon Sill Complex, and related porphyritic diabase dykes. Quaternary deposits form a discontinuous cover over the belt.

Metavolcanic Rocks

Ultramafic metavolcanic rocks occur as a flow unit interbedded with mafic metavolcanic rocks in the Whitton assemblage. Two small, poorly exposed outcrops contain spinifex-textured flow with relict olivine crystals up to 3 cm long, but no well-defined flow morphology. Two outcrops of massive, medium-grained peridotite occur along strike, and probably represent a cumulate portion of the flow. The peridotite lies north of the spinifex outcrops, indicating tops to the south. This unit was traced by airborne magnetic data to the southwest (OGS 2000).

The mafic metavolcanic rocks are predominantly pillowed to massive basaltic flows with subordinate pyroclastics. Pillows are commonly amygdaloidal, and poorly shaped and flattened, resulting in a limited number of top determinations. Massive flows are generally fine to medium grained with occasional gabbroic textured flows. Distinct gabbroic textured flows and pillowed flows with plagioclase phenocrysts up to 6 cm are present in scattered locations. The plagioclase occurs as disseminated grains, and as irregular bands and clots. On the northern edge of the belt, the massive plagioclase-bearing flows grading into pillowed flows with bands and clots of plagioclase phenocrysts probably represent flow segregation within massive lava tubes. Similar plagioclase porphyritic units were observed north of Whitton Lake and in two separate horizons north of Heaven Lake. The coarser fragmental units scattered along the western margin of the belt are a mixture of pyroclastic rocks and deformed massive to pillowed flows.

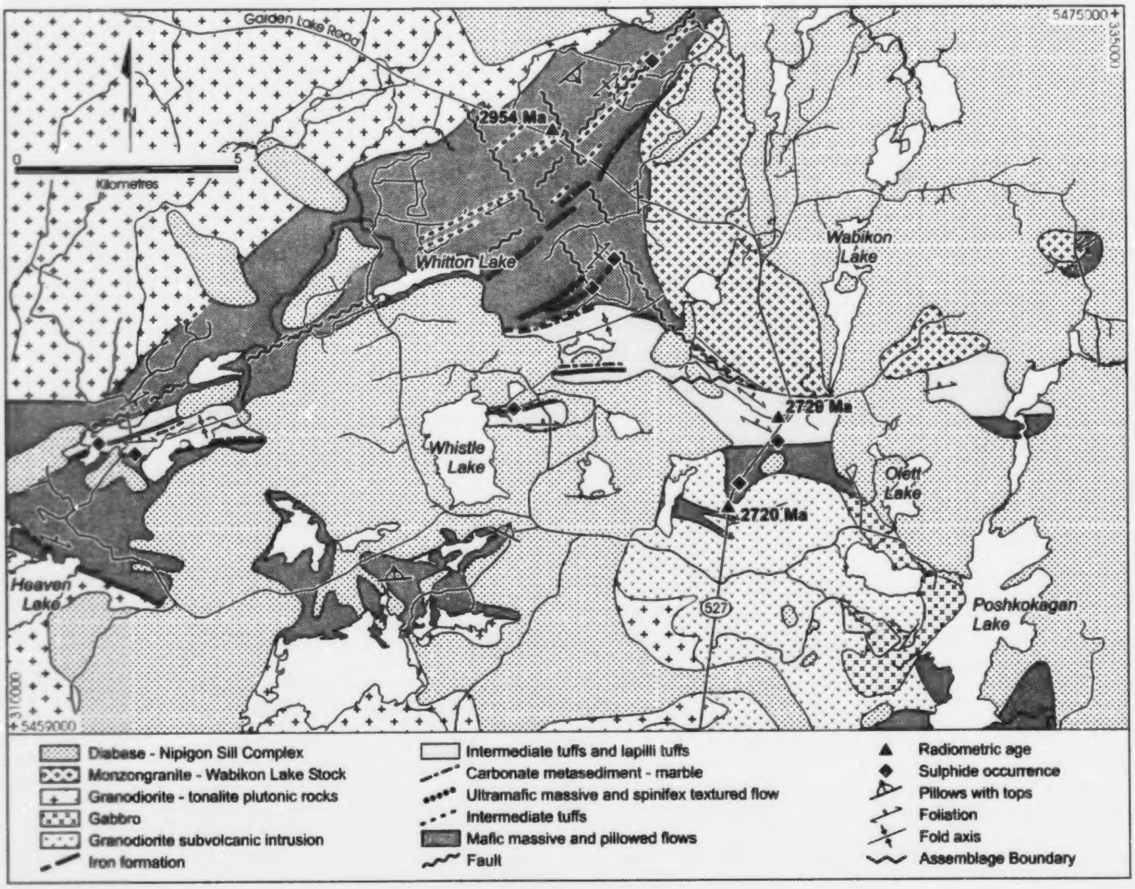

Figure 17.1. Geology of the eastern half of the Heaven Lake greenstone belt.

The Whitton assemblage intermediate metavolcanic rocks are light grey to buff, fine- to very fine-grained tuffs with up to 15% subangular to subrounded quartz phenocrysts. These tuffs form up to 2 m thick units interbedded with the basaltic flows of the lower/northern portion of the assemblage. One of these units along the Garden Lake road has a radiometric age of 2953 Ma (Tomlinson, in press). A thickening of the intermediate tuffs interbedded with the iron formation and carbonate metasedimentary rocks southeast of Whitton Lake is the result of structural repetition. Whistle assemblage intermediate metavolcanic rocks are light grey-brown, buff to grey-green, fine- to medium-grained tuffs, crystal tuffs, and crystal-lapilli tuff in beds 0.25 to 1.0 m thick. The crystal tuff is composed subangular, light blue quartz and/or white feldspar phenocrysts in a fine-grained groundmass. Crystal-lapilli tuffs consist of crystal tuff groundmass with lapilli of similar composition and dark flattened wispy fragments commonly metamorphosed to phyllosilicate. Along Highway 527, the overall crystal abundance and bed thickness decrease from south to north in the area, suggesting stratigraphic tops to the north. An intermediate quartz crystal-rich tuff from the northern series of outcrops along Highway 527 has a radiometric age of 2729 Ma (Tomlinson, in press).

Metasedimentary Rocks

The metasedimentary rocks consist of interflow oxide facies iron formations and minor interflow cherty metasediments and carbonate metasediments. Oxide facies iron formations consist of medium-bedded, 0.25 to 3 m wide units of grey chert and dark to black magnetiferous chert. The thickest iron formations are in contact with the felsic plutonic rocks along the logging road north of the Garden Lake road, south of the komatiite, north of Heaven Lake, and east of Whistle Lake. The iron formations south of the komatiite and north of Heaven Lake have basaltic footwalls and intermediate hangingwalls and are interpreted to be part of the Whitton assemblage. The iron formation east of Whistle Lake is hosted by intermediate tuffs, and is considered to be part of the Whistle assemblage. Rare, grey, 0.1 to 0.25 m thick, interflow cherty metasediments may be either deformed quartz veins or highly attenuated portions of oxide facies iron formations.

The carbonate metasedimentary rock is exposed southeast of Whitton Lake. The unit is light orange-brown to grey, calcite and minor iron carbonate with 0.5 to 1.0 cm thick, dark grey siliceous bands. These bands have a positive relief, possibly defining open- to isoclinally folded bedding. Rare siliceous bands contain magnetite and trace to 1% very fine-grained pyrite and pyrrhotite.

Minor, less than 0.25 m thick, interflow metasedimentary bands, distinguished from the pyroclastic units by the garnet, biotite and muscovite content, are present in scattered locations in the Whitton assemblage. A finely bedded light green to reddish green-grey argillite is exposed on the logging road south of Wabikon Lake.

Felsic Intrusions

Granodiorite intrudes the mafic metavolcanic rocks west of Poshkokagan Lake. The intrusion is dominantly granodiorite in composition, but ranges from monzogranite to tonalite. Subdivision of the granodiorite is based on grain size variations and differences in weathering style. The dominate rock type has 10 to 20% blue quartz phenocrysts visible on the weathered surface, and is a massive, non-porphyritic, coarse-grained rock with 5 to 10% fine-grained amphibole, and ubiquitous trace to 1% fine-grained, disseminated pyrite. Quartz porphyry is characterized by a decrease in quartz phenocryst content and grain size. A feldspar porphyry variant is characterized by a decrease in grain size, absence of quartz phenocrysts, and the presence fine- to medium-grained feldspar phenocrysts. A quartz-feldspar porphyry forms dykes consisting of medium-grained phenocrysts in a fine-grained groundmass, with rare dark coloured fragments less than 1 cm wide. Texture and composition commonly vary subtly over several metres across an outcrop, but some sharp contacts with several later fine-grained varieties crosscutting the granodiorite are also present. A sample from the northwestern portion of this unit has a 2720 Ma age (Tomlinson, in press), indicating that this unit is part of the Whistle assemblage.

Mafic Intrusions

Gabbro intrusions occur west of Poshkokagan Lake, and on the west end of Whitton Lake. The medium-grained, massive gabbro west of Poshkokagan Lake occurs as a massive body, and forms dykes intruding mafic metavolcanic rocks and granodiorite in the southeastern portion of the belt. The gabbro dykes in the granodiorite commonly contain subangular to rounded blocks of granodiorite. In two outcrops, blocks of granodiorite have disintegrated into grains of quartz and feldspar within an altered dioritic matrix. A leucocratic, massive, medium- to coarse-grained gabbro is present on the west shore of Whitton Lake. This unit also outcrops on an island and on the northwest shore of the lake where it is highly sheared and composed of chlorite, epidotized feldspar and subhedral amphibole. Contact relationships with the surrounding rocks are not known.

Felsic Plutonic Rocks

Felsic plutonic rocks bound the belt, and are composed of massive to weakly foliated monzogranite to granodiorite with minor tonalite. Rare dykes of tonalite to granodiorite intrude the margins of the belt. A weakly foliated hornblende bearing monzogranite, the Wabikon Lake Stock, forms the northeastern margin of the belt. The stock has a continuous, megacrystic border phase consisting of randomly oriented, 1.0 to 2.5 cm euhedral laths of potassium feldspar. This border phase occasionally occurs as dykes cutting both the metavolcanic rocks and foliated tonalite dykes within the metavolcanics. An intrusive breccia with a monzogranite matrix is present along the contact between the stock and the rocks of the belt.

Sibley Group Metasedimentary Rocks

A stromatolitic dolomitic limestone horizon (*circa* 1300 Ma) metamorphosed by a diabase sill produced a fine-grained, white marble exposed along the south shore of a small lake, northwest of Olett Lake. Trace, disseminated, very fine-grained, grey metallic mineral, possible a copper-bearing mineral, is present. This unit has a flat orientation and is relatively undeformed, with no associated iron formation, distinguishing it from the >2900 Ma carbonate metasedimentary rocks.

Structural Geology

Bedding and foliations in the metavolcanic and metasedimentary rocks of the northern portion of the Whitton assemblage generally strike northeast with steep south to vertical dips. Rare pillow tops in this part of the assemblage, and architecture of the komatiite flow, indicate a south-facing direction. Rare pillow tops in the flows along the southern margin of the belt indicate north-facing directions. The northern Whitton assemblage is capped by a komatiite–iron formation–marble succession. The carbonate metasediment is not exposed to the west, but a similar unit is reported in drill logs (e.g., Miller 1981). A similar unit is also reported northeast of Whistle Lake (Smith 1995). These "limestone" units are assumed to be >2900 Ma carbonate metasedimentary rocks equivalent to the carbonate metasediment exposed in outcrop. This repetition of the marble to the south is interpreted to indicate an east-trending fold axis between the two units.

The location of the fold axis is obscured by the diabase sills covering the units in the centre of the belt. Porphyritic basalt flows are present in the northern corner of the belt, north of Whitton Lake, and in two locations north of Heaven Lake, but can not be correlated. The iron formations south of the komatiite and north of Heaven Lake have similar stratigraphic positions, with a reversal in the footwall, suggesting location on opposite sides of the fold axis. A combination of the position of the iron formations, porphyritic flows and marble are interpreted to define an east-trending fold axis located north of Whistle Lake.

The radiometric ages of the intermediate tuffs located along the Garden Lake road and along Highway 527 indicate a tectonic break in the belt. Positioning of the fold axis north of Whistle Lake means that the younger Whistle assemblage forms the core to the belt. The Whistle assemblage consists of the intermediate tuffs along the highway, extending to the east under the diabase and to the west as far as Whistle Lake, and the granodiorite. The basalt flows along the south side of the belt are part of the older Whitton assemblage, although the mafic metavolcanic rocks immediately south of the intermediate tuff along the highway could be part of either assemblage, as the contact relations with the intermediate tuffs are not known. The assemblage boundary has been tentatively placed northwest of the highway and south of the granodiorite, with westerly trends.

A higher degree of strain is evident in the metavolcanic rocks along the eastern and western margins of the belt. Foliation directions along the eastern margin are subparallel to the contact of the Wabikon Lake Stock. Emplacement of the stock also resulted in the development of near gneissic textures in the metavolcanic rocks. The metavolcanic rocks in the western end of the belt rarely display any primary textures and a variation in foliation orientation reflects the shape of the bounding plutonic rocks.

A number of late brittle features are present. A northeast-trending fault following the length of Whitton Lake is defined by a series of electromagnetic anomalies and the topographic alignment. Continuation of this fault to the northeast is evident in the shearing of the intermediate tuffs and adjacent mafic metavolcanic rocks. A series of northwest-trending fault with a sinistral offset are interpreted to have offset stratigraphy in the northern portion of the Whitton assemblage.

Metamorphism

The metamorphic grade varies from greenschist facies in the core of the belt to amphibolite facies at the contact with the plutonic rocks. Intrusion of the Wabikon Lake Stock appears to have resulted in a hornfelsing of the mafic metavolcanic rocks and a resulting well-developed magnetic halo and a strong fabric paralleling the intrusive contact. Intrusion of the granodiorite resulted in a very localized amphibolite facies metamorphism.

Alteration and Mineralization

A number of brecciated ankerite-calcite veins are present along the contact between the granodiorite and the mafic metavolcanic rocks on Highway 527. The veins consist of tabular to irregular masses of ankerite/dolomite rimmed by calcite in a matrix of chlorite and/or anthophyllite. Hematite staining of the calcite yields dark red patches. Minor, very coarse-grained pyrite is present in one location.

The intermediate crystal tuff exposed along Highway 527 is cut by northwest-trending fractures and shears containing quartz and/or chlorite with pyrrhotite, pyrite, chalcopyrite, galena, and malachite. An assay of the sulphide-rich fracture exposed on the highway returned 10 464 ppm Zn, 505 ppm Cu and not detectable Au or Ag. An assay of the best sample from the pit 50 m east of the highway returned 223 ppm Zn, 4559 ppm Cu, 3.5 ounces of silver per ton and no detectable Au. There is no strong pervasive alteration in the intermediate tuffs in this area indicative of VMS-style hydrothermal alteration.

Two northwest-trending, sulphide-rich shears cut pillowed to massive basalt intruded by granodiorite dykes, along Highway 527 approximately 1400 m southwest of the intermediate tuffs discussed above. The shears contain minor stringer pyrite, pyrrhotite and minor chalcopyrite, and the best assay returned 202 ppm Zn, 4324 ppm Cu, 0.04 ounces of gold per ton and no detectable Ag. This mineralization is interpreted as related to the granodiorite, and part of the same mineralizing system as exposed in the intermediate tuffs to the north.

Sulphide mineralization is associated with the iron formations south of the komatiite, north of Heaven Lake and east of Whistle Lake. In two locations, the sulphide occurs as disseminated to stringer pyrite and pyrrhotite in fractures and along bedding in the iron formation. The best assay is from the sulphide mineralization south of the komatiite, with 4283 ppm Zn, 464 ppm Cu, and no detectable Au or Ag. A 0.5 to 1.0 m thick, massive to semi-massive lens of pyrite with minor pyrrhotite and chalcopyrite is located adjacent to the iron formation in a trench east of Whistle Lake. The best assay from this lens is 1120 ppm Zn, 942 ppm Cu, and no detectable Au or Ag. These sulphides appear to be primary, but deformation has partially remobilized the sulphides into fractures.

A sheared, sericitic intermediate tuff is exposed in two locations approximately 1500 m apart along strike, in the area north of the Garden Lake road. The tuff contains up to 5% disseminated, fine-grained pyrite.

TECTONIC DISCUSSION

The Heaven Lake belt contains a mixture of Mesoarchean rocks, Whitton assemblage, and Neoarchean rocks, Whistle assemblage. The komatiite-carbonate-iron formation sequence in the Whitton assemblage has been correlated with a similar sequence in the Lumby Lake belt (e.g., Tomlinson et al. 1998). Isotopic data indicate a similar juvenile signature, indicative of a lack of older continental basement during formation, in both the Heaven Lake and Lumby Lake belts (Tomlinson, in press). The Whistle assemblage is similar in age to the intermediate metavolcanic rocks in the Elmhirst–Rickaby volcanic centres, east of Lake Nipigon (G.M. Stott, personal communication, 2000). The metavolcanic rocks of both the Whistle assemblage and the Elmhirst–Rickaby are north-facing supporting the correlation, but additional work is required.

The relationship of the Heaven Lake belt with the Garden Lake belt to the north and the Lac des Iles belt to the south is not clear. A lack of felsic to intermediate metavolcanic rocks in the Garden Lake belt is similar to the Whitton assemblage, but there is no carbonate or ultramafic unit. The age of the metavolcanic rocks in the Garden Lake belt is not known, but the minimum age is 2706 Ma from a crosscutting felsic dyke (Tomlinson et al. 1998). A sample was recently collected for a radiometric age determination for the metavolcanic rocks of the Garden Lake belt (K. Tomlinson, personal communication, 2000). The Lac des Iles belt has an intermediate metavolcanic unit, and lacks carbonate and ultramafic units, comparable to the Whistle assemblage. None of the metavolcanic rocks of this belt has a radiometric age, and the minimum age is 2684 Ma from the conglomerates to the south (Tomlinson et al. 1998). There are three porphyritic mafic flows in the Lac des Iles belt, comparable to the porphyritic flows of the Whitton assemblage, suggesting a complex tectonic history.

OTH GEOPHYSICAL SURVEY

The Heaven Lake belt was covered by the Garden–Obonga area combined total magnetic and frequency-domain EM survey by Dighem (OGS 2000). Magnetic data, particularly in the form of the second vertical derivative of the total field, are useful in delineating the units with a higher magnetic susceptibility such as the diabase, komatiite and iron formations. The EM anomalies were useful in correlating the widely separated segments of the iron formation and defining the late brittle features.

RECOMMENDATIONS

A radiometric age determination from the intermediate tuffs north of Heaven Lake would aid in the formulation of a stratigraphic framework for the belt.

Past exploration of the intermediate tuff exposed on Highway 527 has been for VMS-style mineralization, but current observations suggest a meso-epithermal style mineralization associated with the granodiorite. A larger-scale program examining gold and base metal potential of the metavolcanic rocks and granodiorite in this area is warranted.

The report of white brucite limestone (Sibley Group?) west of Wabikon Lake, in diamond drill logs in the assessment files (Koosell, 1964), suggests that there may be additional occurrences of marble potentially suitable as dimension stone. Prospecting concentrating on the basal contacts of the diabase sills in the area around Olett and Wabikon lakes may uncover occurrences.

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18. Project Unit 00-08. Geology of the Lac des Iles Greenstone Belt, Central Wabigoon Subprovince

T.R. Hart[1] **and C.A. MacDonald**[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Mapping of the Lac des Iles greenstone belt (Figure 18.1) evaluated 1) the economic potential of the belt in combination with the Ontario Treasure Hunt (OTH) Garden–Obonga geophysical survey (OGS 2000), and 2) the position of the belt within the tectonostratigraphic framework of the central Wabigoon subprovince as proposed by the Western Superior NATMAP project. This project characterized the metavolcanic and intrusive rocks of the Lac des Iles belt and their relationship to mineralization. Mineralization includes quartz and quartz-tourmaline veins with anomalous to weak gold mineralization, and sulphide facies iron formations traced across the belt by the associated electromagnetic (EM) anomalies. The Lac des Iles belt is tentatively correlated with the metavolcanic rocks of the Elmhirst–Rickaby volcanic centres, located to the north of the Beardmore–Geraldton belt.

The Lac des Iles greenstone belt is located approximately 90 km north of Thunder Bay and west of Lake Nipigon. Previous mapping was by Pye (1968) on a 1:31 680 scale, and by Sage et al. (1974), and Sage (1998) on 1:126 720 scale. Exploration and prospecting was initially conducted in the 1930s, but further exploration did not occur until after the discovery of mineralization at Lac des Iles in 1963, and the building of Highway 527. Past exploration has concentrated on the drilling of scattered holes on EM conductors and prospecting for gold.

GENERAL GEOLOGY

The belt is composed of a northeast-trending, south-facing sequence of metavolcanic rocks divided into a northern and southern assemblage. The northern assemblage consists of mafic metavolcanic flows overlain by intermediate pyroclastics, and capped to the south by a sulphide facies iron formation. The southern assemblage consists of mafic metavolcanic flows, pyroclastic and volcaniclastic units, with minor thin intermediate pyroclastics. Gabbro sills intrude the mafic metavolcanic rocks of both assemblages, and a layered gabbro intrudes the eastern edge of the southern assemblage. Felsic plutonic rocks bound the belt to the north, and intruded the core of the belt as a small feldspar porphyritic granodiorite. Conglomerates of the Quetico metasedimentary sequence (2784 Ma; Tomlinson et al. 1998) bound the belt to the south. Discontinuous diabase sills of the Proterozoic Nipigon Sill Complex, and related porphyritic dykes, intrude or overlie all other units in the belt. Quaternary deposits form a discontinuous cover over the belt. The metamorphic grade varies from greenschist facies for most of the belt to amphibolite facies along the northern margin with the felsic plutonic rocks.

Metavolcanic Rocks

The mafic metavolcanic rocks of the northern assemblage are predominantly pillowed to massive basaltic flows with minor mafic tuffs and lapilli tuffs. Pillows are poorly shaped and flattened to varying degrees, resulting in a limited number of top determinations indicating tops to the south. Massive flows are commonly medium grained and amphibole rich, and difficult to distinguish from mafic sills. Distinct gabbroic textured flows, with up to 6 cm plagioclase phenocrysts occur north of Rinker Lake and west of Vanderbrooks Lake. West of Vanderbrooks Lake, a flow contains irregular bands and clots of phenocrysts resembling the porphyritic mafic flow in the Heaven Lake belt. Mafic tuffs and lapilli tuffs are more prominent in the southern portion of the assemblage, between the intermediate tuffs and the sulphide facies iron formation.

Mafic metavolcanic rocks of the southern assemblage consist of massive to pillowed flows, pyroclastic and volcaniclastic rocks. The massive flows range from aphanitic to medium- to coarse-grained amphibole-rich and finer-grained flows, which commonly have amygdaloidal flow tops. Pillows may be up to 3 m in length and 0.5 m wide with amygdaloidal margins, easily confused with massive flow tops in poor exposures. A massive, gabbroic textured flow with 1 to 3 cm feldspar phenocrysts,

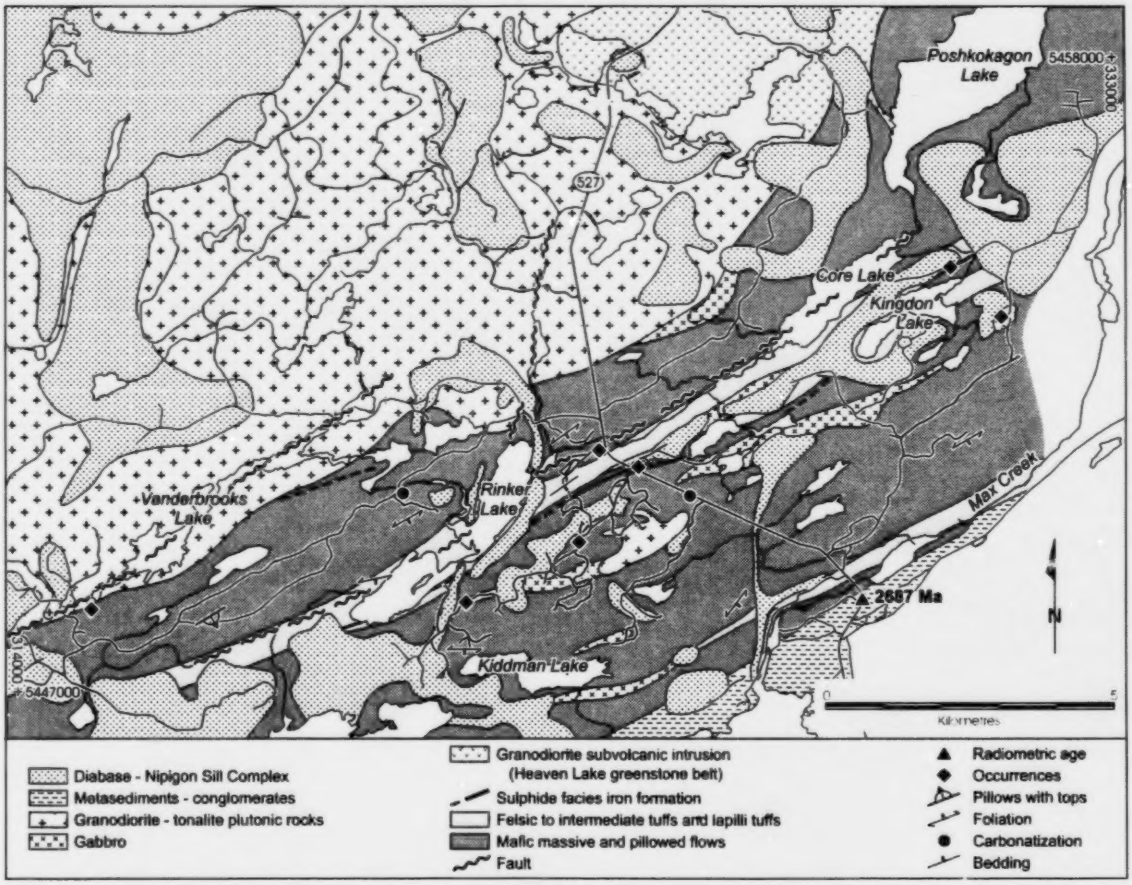
Poshkokagon Lake
5458000
333000
527
Core Lake
Kingdon Lake
Rinker Lake
Vanderbrooks Lake
Max Creek
2687 Ma
N
Kiddman Lake
314000
5447000
0
5
Kilometres
Diabase - Nipigon Sill Complex
Metasediments - conglomerates
Granodiorite - tonalite plutonic rocks
Gabbro
Granodiorite subvolcanic intrusion (Heaven Lake greenstone belt)
Sulphide facies iron formation
Felsic to intermediate tuffs and lapilli tuffs
Mafic massive and pillowed flows
Fault
Radiometric age
Occurrences
Pillows with tops
Foliation
Carbonatization
Bedding

Figure 18.1. Geology of the eastern portion of the Lac des Iles greenstone belt.

similar to the porphyritic flow north of Rinker Lake, is located south of Kingdon Lake. The pyroclastic and volcaniclastic rocks are most prominent in two bands in the centre and along the southern side of the assemblage. The pyroclastic rocks range from tuff to lapilli tuff with clastic material of dominantly mafic composition. The volcaniclastic rocks include pillow breccias and tuff breccia, which may contain significant proportions of intermediate to felsic clasts.

Intermediate metavolcanic rocks commonly occur as minor tuff to lapilli tuff units in both assemblages, and as a prominent sequence in the northern assemblage. An approximately 300 m thick sequence of predominantly tuff and minor flow bounded by lapilli tuff, occurs towards the top of the northern assemblage. In the best exposures located west of the highway and east of Rinker Lake, the most prominent unit is a massive to weakly foliated quartz crystal-rich ash tuff. The lower lapilli tuff units contain feldspar and minor quartz clasts in a very fine-grained groundmass. The upper lapilli tuff units, along the southern contact, have a mixture of feldspar porphyritic and quartz porphyritic clasts in a chloritic matrix. Variation in clast size, and accumulation of pumiceous clasts to the south, indicate tops to the south. In the southern assemblage, tuff units increase in thickness and abundance towards the south. The lapilli tuffs north of Max Creek consist of predominantly medium-grained, white feldspar clasts in a very fine-grained, light green groundmass. Rare, 20 to 30 cm thick, quartz porphyritic units are present in the southern assemblage, with one of the few exposures containing a very fine-grained tuff in contact with the granodiorite.

Metasedimentary Rocks

The metasedimentary rocks consist of interflow sulphide facies iron formations and argillaceous metasediments. Sulphide facies iron formations are exposed along Highway 527 and on a logging road west of Vanderbrooks Lake. On Highway 527, the iron formation consists of massive pyrite and minor pyrrhotite underlain by to the north by stringer pyrrhotite and pyrite, and a 25 cm thick grey to white chert bed. The mafic metavolcanic rocks underlying the stringer sulphides are intensely altered to chlorite, and contain a number of 5 to 10 cm garnet-chlorite bearing argillaceous beds and two 10 cm thick quartz porphyritic felsic tuffs. The northeast strike extension of this sulphide iron formation is exposed in contact with a diabase sill, along a logging road north of Kingdon Lake. A separate sulphide iron formation west of Vanderbrooks Lake consists of irregular pods of semi-massive pyrite up to 20 cm wide associated with lenses of chert. This unit is located to the north of the porphyritic mafic flow with the deformed and metamorphosed metavolcanic rocks along the contact with the felsic plutonic rocks. Thin argillaceous interflow metasediments, similar to the units underlying the iron formation, separate mafic metavolcanic units in some locations.

Mafic Intrusions

Gabbroic units are common in both assemblages, and some of the units are interpreted to be subvolcanic sills. The most prominent gabbro sills are observed close to the margins of the belt, west of Core Lake and south of Kiddman Lake. These units consist of medium- to coarse-grained hornblende gabbro, and are massive to weakly foliated. Massive, medium- to coarse-grained hornblende gabbro units are also prominent in a band along the centre of the belt. These central units may be related to the assemblage boundary and the intrusion of the granodiorite phase of the felsic plutonic rocks.

A massive to layered, hornblende gabbro is located at the eastern end of these central mafic intrusions, and is exposed in a series of outcrops covering an approximately 1000 m^2 area along a logging road southeast of Kingdon Lake. The southern contact is sharp and crosscutting, with a border phase composed of a medium- to coarse-grained hornblende gabbro containing irregular, up to 10 cm, very coarse-grained pods of gabbro. An irregular to sheared contact occurs between the border phase and a layered sequence. The layered sequence is a 2 to 3 m thick series of 0.5 to 0.75 cm alternating layers of medium- to coarse-grained feldspar and hornblende. The layered sequence has a relatively sharp contact with a massive, medium- to coarse-grained hornblende gabbro to the north. A diabase sill overlies the gabbro to the north. All three parts of the gabbro contain trace to 1% fine- to very fine-grained, disseminated pyrite and pyrrhotite.

Felsic Plutonic Rocks

The belt is bounded to the north by massive to weakly foliated granodiorite to tonalite with minor monzogranite. A feldspar porphyritic granodiorite intrudes the metavolcanic rocks near the base of the southern assemblage, southeast of Rinker Lake. The granodiorite is composed of 3 to 9 mm laths of white to grey feldspar in a fine-grained groundmass of quartz, feldspar and biotite. Contacts with the metavolcanic rocks are sharp and crosscutting. The irregular distribution of outcrops indicates that the granodiorite forms sills in the metavolcanic flows. This unit may be present over a wide area as dykes, such as the narrow, fine-grained granodiorite dyke observed east of the highway. A separate, fine- to medium-grained feldspar porphyritic granodiorite intrudes the mafic to intermediate metavolcanic rocks in the area north of Max Creek.

Structural Geology

Bedding and foliations in the metavolcanic and metasedimentary rocks generally strike northeast with steep south to vertical dips. Rare pillow tops and graded bedding in pyroclastic and volcaniclastic units indicate a south-facing direction throughout the belt. The sulphide facies iron formation and associated tuffs and argillaceous metasediments are interpreted to represent a northeast-trending tectonic boundary separating the northern and southern assemblages. The granodiorite phase of the plutonic rocks has intruded the metavolcanic rocks close to this break. Gabbro sills and the layered gabbro are also located along this proposed assemblage boundary.

Brittle features within the belt are subparallel to the foliations and the assemblage boundary, and have influenced the orientation of the diabase sills. Smaller-scale brittle features control the orientation of the quartz veining throughout the belt.

Alteration and Mineralization

A zone of intense carbonatization is present in the mafic metavolcanic rocks along the logging road northwest of Rinker Lake. The pillowed flows are light grey to brownish grey and intensely carbonate flooded, but relatively undeformed. There are also a number of white quartz-tourmaline veins with variable amounts of very coarse-grained pyrite cutting the carbonatized flows. A 1 to 2 m thick, massive iron carbonate zone caps the alteration to the south, interpreted to indicate a conformable style of alteration possibly synvolcanic in origin. The intense carbonatization and 10 to 20 cm wide bands of iron carbonate are present for approximately 2 km along strike to the west.

A second zone of intense carbonate alteration is exposed in a rock cut along the highway, south of the iron formation and along strike with the granodiorite. The zone is 4 to 5 m thick and flooded by iron carbonate. The host rock is probably a mafic metavolcanic rock, but this style of alteration is also common in ultramafic rocks.

Quartz and quartz-tourmaline veins are common in the belt, and are especially prominent in the southern assemblage. Both vein types are commonly hosted by northeast-trending fractures in massive flows and gabbro sills. The quartz veins consist of white to light grey quartz with variable amounts of calcite, iron carbonate and/or pyrite and pyrrhotite. Numerous quartz veins have been exposed in the rock cuts during road construction. Quartz-tourmaline veins usually lack carbonate and sulphide, but may have minor chlorite associated with the tourmaline. Tourmaline is also common in fractures, as rosettes of very fine needles, alone or with chlorite. An area with a high density of veining lies between Rinker and Kiddman lakes, and may be related to the granodiorite. The quartz veining of the Fat Beagle occurrence hosts erratic gold mineralization (Christiansen 1996). The results of all vein samples taken during this project are pending.

Disseminated pyrite and pyrrhotite with minor malachite are present in sheared mafic metavolcanic rocks southeast of Rinker Lake, along a logging road. The shearing strikes to the northeast. This type of mineralization is exposed in two apparently unrelated locations along the road. Assay results for sampling during this project are pending.

The sulphide facies iron formation on Highway 527 is composed of pyrite and pyrrhotite, with footwall chloritic alteration similar to that observed in a volcanogenic massive sulphide hydrothermal system. Detailed sample results of the sulphides are pending, but initial assay results of the stringer sulphides are not anomalous in either base or precious metals. The iron formation can be traced to the northeast, correlating with the sulphide horizon north of Kingdon Lake, and southwest by the presence of EM anomalies (OGS 2000). North of Kingdon Lake, the sulphides consist of massive to semi-massive pyrite and pyrrhotite along the contact of a diabase sill. The character of the mineralization is not the same as on the highway, probably a result of remobilization along the diabase contact. Assay results for sampling during this project are pending.

The sulphide facies iron formation exposed along the northwestern edge of the belt is composed of massive to semi-massive lenses of coarse-grained pyrite and pyrrhotite. The extent of this unit is not known, but appears to correlate with a series of EM anomalies to the northeast, where drilling indicates the presence of massive sulphides (Halladay 1972). Assay results for sampling during this project are pending.

The layered hornblende gabbro on the eastern edge of the belt has trace to 1% disseminated, fine- to very fine-grained pyrite and pyrrhotite. Concentrations of sulphides occur in fractures and are most prominent in fractures cutting very coarse-grained pods of the border phase. The sulphides are mainly pyrite and pyrrhotite with trace amounts of chalcopyrite. Assay results for samples from this area are pending.

OTH GEOPHYSICAL SURVEY

The Lac des Iles belt was covered by the Garden–Obonga area combined total magnetic and frequency domain EM survey by Dighem (OGS 2000). Magnetic data, particularly in the form of the second vertical derivative of the total field, are useful in delineating the units with a higher magnetic susceptibility, such as the diabase and iron formations. The EM anomalies were useful in correlating the widely separated segments of the sulphide facies iron formation.

TECTONIC DISCUSSION

The metasedimentary and greenstone belts immediately to the south of the Lac des Iles have been correlated with the Geraldton–Beardmore belt based on continuity of the airborne magnetic patterns across the southern end of Lake Nipigon. The metavolcanic rocks of the Lac des Iles belt are tentatively correlated with the metavolcanic rocks to the north of the Beardmore–Geraldton belt, on the south side of the Elmhirst–Rickaby volcanic centres (G.M. Stott, personal communication, 2000). This correlation, and the abundances of quartz and quartz-tourmaline veins, suggest that the Lac des Iles belt has the same potential to host gold mineralization as the Elmhirst–Rickaby area ("Northern Felsic Volcanic Dominated Belt" of Mason and McConnell (1983)).

The Lac des Iles and Heaven Lake belts strike east-northeast and potentially join in the area covered by the diabase sills. The abundance of intermediate tuffs in the northern assemblage of the Lac des Iles belt and the Whistle assemblage of the Heaven Lake belt favour the correlation of these two assemblages. The occurrence of porphyritic mafic flows in the northern assemblage and Whitton assemblage of the Heaven Lake belt would tend to contradict this interpretation. Additional work using lithogeochemistry, and radiometric age determinations, is required.

RECOMMENDATIONS

Further exploration of the sulphide facies iron formation is warranted. The unit has a pronounced chloritic footwall alteration and could grade laterally into a unit containing base metal sulphides. The iron formation is delineated by a string of EM anomalies, and has only been tested by a few scattered diamond drill holes.

Gold mineralization is associated with quartz veining in one occurrence in the belt, and may be present in other locations. Areas that should be examined are north of Kiddman Lake and between Kingdon Lake and Max Creek.

Additional work is required to establish the platinum group element potential of the layered gabbro on the eastern edge of the belt. The gabbro contains both fracture hosted and disseminate sulphide mineralization of unknown extent. The size of the gabbro is also not well established, and additional prospecting is required to the east of the logging road.

A radiometric age determination is required to help place this belt in the tectonostratigraphic framework of the central Wabigoon subprovince.

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19. Project Unit 00-012. Magnetic Susceptibility: Selected Applications to Geological Studies and Mapping

G.P. Beakhouse[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The development of instrumentation that permits the determination of magnetic susceptibility in the field has been found to have many applications to geological investigations and mapping. This technology was originally applied to investigation of granitoid rocks associated with the Hemlo greenstone belt, leading to the development of a potential means of rapidly identifying highly oxidized intrusive rocks that may play a crucial role in metallogenesis and have application to mineral exploration (Beakhouse, in press). Magnetic susceptibility has also been routinely used in the first year of a multi-year greenstone belt mapping project (Beakhouse, this volume) and other reconnaissance studies, resulting in the recognition of numerous additional applications of this technology. The purpose of this contribution is to present a preliminary assessment of selected applications to geological mapping and investigations.

The magnetic susceptibility of a rock is a volume percent weighted average of the magnetic susceptibility of its constituent minerals. The common rock-forming minerals include diamagnetic minerals with negligible, negative magnetic susceptibilities that do not contribute appreciably to rock magnetism (e.g., quartz, feldspar), paramagnetic minerals with positive, weak magnetic susceptibilities that subtly contribute to rock magnetism (e.g., olivine, pyroxene, amphibole, biotite, garnet) and ferrimagnetic minerals with moderate to high, complex magnetic susceptibilities (e.g., magnetite, pyrrhotite) (Klein and Hurlbut 1977). Consequently, in the absence of unusual mineralogy, magnetic susceptibility can be regarded, to a first approximation, as a measure of the magnetite and, in some cases, pyrrhotite content of a rock.

INSTRUMENTATION

All measurements were performed with a KT-9 magnetic susceptibility meter manufactured by Exploranium Radiation Detection Systems. This instrument is capable of measuring true magnetic susceptibilities in the range 0.01 x 10^{-3} to 999 x 10^{-3} (dimensionless SI units), which was found to be adequate for all situations other than massive magnetite layers in ironstone units. The unit was operated in the "pin-mode" in order to minimize errors introduced due to measurement on uneven surfaces (Exploranium Radiation Detection Systems, KT-9 Users Guide).

APPLICATION TO GEOLOGICAL INVESTIGATIONS

Distinction of Granitoid Suites

The amount of magnetite in a granitoid rock is a function of oxidation state and total Fe content, and as such can be used to characterize and distinguish different granitoid suites and/or units. It is particularly useful to distinguish dike phases that may be texturally distinct from the parental pluton. Iron-rich and iron-poor end members may have higher and lower magnetic susceptibilities as a function of their Fe content but, if fO_2 is consistently buffered within the suite, may vary systematically and define coherent trends in plots of magnetic susceptibility *versus* total Fe or other indices of fractionation (*see* discussion *in* "Redox Characterization of Granitoid Suites").

Secondary processes that either create or destroy magnetite can modify the magnetic susceptibility. The principal mechanisms whereby magnetite is destroyed (decreasing magnetic susceptibility) include secondary oxidation of magnetite to hematite and sulphidation reactions. Neither of these processes has operated on a large scale in any of the plutons investigated to date but both have been recognized locally. As discussed in a subsequent section, the potential to use magnetic susceptibility to identify and map these types of alteration has application to mineral exploration. The only secondary process identified to date that is capable of enhancing the magnetic susceptibility of granitoid rocks is the exsolution of Fe-Ti oxides from ferromagnesian minerals accompanying phase transformations. This process has to date only been recognized in plutons with abundant primary magnetite, with secondary magnetite representing less than 2 to 3% of the total magnetite. In these cases, the secondary magnetite is interpreted to have a negligible effect on the measured magnetic susceptibility. These possible complications should always be evaluated but have not been found to be widespread problems in this investigation, and measured magnetic susceptibilities in late plutons are interpreted to reflect primary magnetite abundance that are functions of total Fe content and magmatic oxidation conditions.

Redox Characterization of Granitoid Suites

A variety of workers have contrasted relatively oxidized, I-type or magnetite-series granitic rocks commonly associated with Cu, Mo and Au deposits with more reduced S-type or ilmenite-series granitic rocks that are associated with Sn and W deposits (Ishihara 1977; Chappel and White 1992). Blevin (1996) demonstrated that magnetic susceptibility, although it is a function of both bulk composition and redox state and can be modified by secondary processes, can be effective in distinguishing these two series.

Within the I-type series, the most highly oxidized plutons may be the most favourable for the formation of magmatic Cu, Mo and Au deposits. This is a consequence of the stabilization of sulphate rather than sulphide under highly oxidizing conditions, which prevents the formation of sulphides that would strip ore metals out of the magma (Carrol and Rutherford 1985). As a result, these metals are available for partitioning into an oxidized magmatic volatile phase evolved at a late stage in the crystallization of the magma. Some gold mineralization in the Superior Province, including the Hemlo gold deposit, is interpreted to be genetically related to oxidized hydrothermal fluids (Cameron and Hattori 1987; Cameron and Carrigan 1987). These authors also regard intrinsically oxidized magmas as the most likely source for such fluids, and Hattori (1987) notes a spatial association between gold deposits and magnetic intrusions.

These observations and interpretations suggest that the oxidization state of plutons may be an important regional metallogenic consideration, which has implications for mineral exploration.

Unfortunately, precise estimation of redox conditions is both difficult and time consuming, generally involving detailed mineral chemistry, including mineral separation and determination of Fe_2O_3/FeO ratios by wet chemistry or Mossbauer spectroscopy. Results of detailed investigations carried out on plutons associated with the Hemlo greenstone belt suggest that it may be possible to gain some insight into the oxidation state of plutons from variation in magnetic susceptibility as a function of other readily acquired (modal analyses, whole-rock total Fe) variables. The results of some aspects of this ongoing investigation (discussed more fully *in* Beakhouse, in press) are summarized briefly below.

Most of the late plutons associated with the Hemlo greenstone belt have mineralogical assemblages typical of I-type granites. The most direct indication of crystallization under relatively oxidizing conditions is the widespread and relatively abundant occurrence of magnetite in all late plutons except the Heron Bay pluton, which is anomalous in this regard. Wones (1989) has proposed that the assemblage titanite + magnetite + quartz is indicative of relatively high oxygen fugacities (intermediate between fayalite-magnetite-quartz and hematite-magnetite buffers). This mineral assemblage is present in all of the late plutons associated with the Hemlo greenstone belt. Magmatic epidote, which is widely distributed in all of the late plutons associated with the Hemlo greenstone belt, is also thought to be indicative of crystallization under relatively oxidizing conditions (Zen and Hammarstrom 1984; Schmidt and Thompson 1996).

These and other characteristics (Beakhouse, in press) suggest that all of the late plutons crystallized under fO_2 conditions at least as oxidizing as the fayalite-magnetite-quartz buffer; however, other evidence suggests that several of the plutons may be even more oxidized. The anomalously highly oxidized plutons include the Cedar Creek and Botham stocks, which occur within several hundreds of metres of the eastern and western ends, respectively, of the Hemlo gold deposit. The Satellite stock, which is similar in most respects to the Cedar Creek stock and lies approximately 4 km north of the deposit, may also be highly oxidized. These plutons are distinguished by their slightly higher whole-rock $Fe_2O_3/(Fe_2O_3+FeO)$ ratio (Table 19.1) and anomalously magnesium-rich ferromagnesian minerals relative to their whole-rock Mg number (Figure 19.1) (cf. Czamanske and Wones 1973). These findings are consistent with the results of a detailed study of the Cedar Creek stock, which indicates magmatic fO_2 intermediate between the nickel–nickel oxide and magnetite–hematite buffers (Cameron and Carrigan 1987). The magnetic susceptibility of these units is comparable to that of several of the more mafic late plutons (e.g., Gowan Lake and Fourbay Lake plutons) but the more leucocratic, iron-poorer nature of the Cedar Creek and Botham stocks suggests that their comparable magnetic susceptibilities require that they have been more highly oxidized. The Terrace Bay batholith in the Terrace Bay–Schreiber greenstone belt is spatially associated with Cu-Mo and Au mineralization (Marmont 1984) and shares the same characteristics. The Otto and Cairo stocks are part of a mildly alkalic magmatic suite that is spatially associated with the Kirkland Lake–Larder Lake fault zone and gold mineralization. Previous investigations indicate that some of the intrusions within this suite are mantle-derived rocks characterized by high intrinsic fO_2 (Rowins, Lalonde and Cameron 1991; Levesque 1994). These plutons have among the highest magnetic susceptibilities measured as part of this investigation, and further suggest that the more highly oxidized plutons associated with gold mineralization may be distinguished on a plot of magnetic susceptibility *versus* $Fe_2O_3^{Total}$ (Figure 19.2).

The foregoing suggests that it may be possible to gain some insight into the oxidation state of granitic plutons by consideration of their magnetic susceptibility as a function of whole-rock total iron, which can be directly measured by readily available, inexpensive X-ray fluorescence analysis or even estimated from modal abundances. Specifically, on a plot of magnetic susceptibility *versus* total iron, plutons may define a series of curvilinear arrays of increasing magnetic susceptibility with increasing total iron content that are characteristics of different buffer assemblages (Figure 19.2). Further studies are in progress to test and further develop this hypothesis, as well as the possible connection between mineralization (Au, Cu, Mo) and oxidized magmatic rocks.

Table 19.1. Summary of characteristics used to infer the fO_2 of plutonic rocks associated with the Hemlo greenstone belt.

Pluton	Fe_2O_3/ FeO[a]	Magnetic Susceptibility ($x10^{-3}$)[a]	Primary Fe-Ti Oxides[c]	Magmatic Titanite[c]	Magmatic Epidote[c]
Black-Pic and Pukaskwa batholiths[b]	0.83 ± .16 (17) 0.54 – 1.08	3.51 ± 3.82 (46) -0.01 – 15.3	Common, minor magnetite	Common, minor	Common, minor
Dotted Lake batholith	0.94 ± .21 (11) 0.51 – 1.40	2.15 ± 2.01 (20) -0.02 – 1.40	Rare, trace magnetite	Common, minor	Common, minor
Heron Bay pluton	0.86 ± .17 (33) 0.41 – 1.43	0.45 ± 0.72 (36) 0.00 – 2.89	Rare, trace magnetite	Ubiquitous, minor	Ubiquitous, minor to abundant
Cedar Lake pluton-Main Phase	0.79 ± .13 (16) 0.50 – 1.06	4.00 ± 3.94 (29) 0.07 – 15.4	Common, minor magnetite	Ubiquitous, abundant	Common, trace to minor
Cedar Lake pluton-Magnetic Phase	1.03, 1.04 (2)	9.43, 10.9 (2)	Ubiquitous, moderately abundant magnetite	Common, abundant	Erratic, minor
Cedar Creek stock	1.21 ± .17 (5) 1.06 – 1.50	13.3 ± 1.3 (5) 11.8 – 14.9	Ubiquitous, abundant magnetite	Common, abundant	Common, minor
Musher Lake pluton	0.67 ± 0.09 (5) 0.57 – 0.78	3.14 ± 1.32 (5) 1.07 – 4.69	Ubiquitous, minor to trace magnetite	Ubiquitous, minor	Ubiquitous, minor
Gowan Lake pluton	0.78 ± .09 (16) 0.58 – 0.94	13.9 ± 5.8 (26) 0.21 – 26.5	Ubiquitous, abundant magnetite/ Common, minor titanomagnetite and ilmenite	Common, minor	Common, minor
Fourbay Lake pluton	0.68, 0.92, 0.94, 0.98 (4)	11.5, 19.0, 23.0, 23.0 (4)	Ubiquitous, abundant magnetite/ minor titanomagnetite and ilmenite	Common, minor	Common, trace

[a] Whole rock Fe_2O_3/FeO (from XRF/wet chemistry) and magnetic susceptibility are reported as follows: average ± 1 standard deviation, number of determinations in brackets followed by the range. Individual sample data are listed for the magnetic phase of the Cedar Lake pluton and Fourbay Lake pluton for which limited data is available.

[b] Characteristics listed are those of the main foliated to gneissic, tonalitic to granodioritic phases only.

[c] All of these minerals have several modes of occurrence but this table refers only to those occurrences that are interpreted to be primary magmatic phases. Each mineral is described in terms of its frequency of occurrence (rare, common, ubiquitous) and characteristic abundance (trace, minor, abundant) in the respective units.

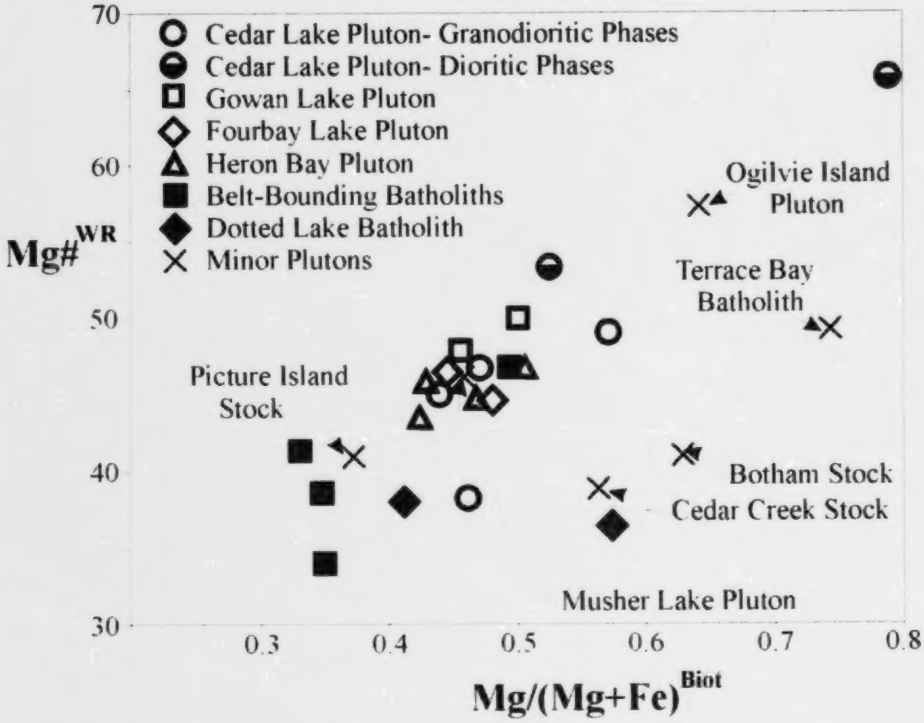


Figure 19.1. Plot of whole rock Mg# *versus* Mg/(Mg+Fe) for corresponding biotite for plutons associated with the Hemlo greenstone belt. The anomalously magnesium-rich nature of biotite from the Cedar Creek and Botham stocks and Terrace Bay batholith are attributed to the intrinsically more oxidized nature of these magmas.

Distinction of Volcanic Series

Preliminary investigations indicate that the magnetic susceptibility of volcanic rocks ranges across four orders of magnitude. This variability arises in large part from the wide range in bulk composition (magnesium-rich basalts through high-iron tholeiites to high-silica rhyolite). The highest magnetic susceptibilities in metavolcanic rocks measured during the course of this work are generally associated with iron-rich tholeiitic basalts. The highest value recorded (256) is for the Boston Creek flow in the Kirkland Lake area but, more typically, maximum values range up to 80-100. More magnesium-rich basaltic rocks have lower magnetic susceptibilities. Felsic volcanic rocks generally have very low magnetic susceptibility (<0.1).

This technology is perhaps most useful for investigations of mafic volcanic-dominated sequences for which magnetic susceptibility ranges across three orders of magnitude within rocks that are megascopically quite similar. The Wabigoon and Brownridge volcanic units in the Wabigoon area (Beakhouse, this volume) are two examples of mafic volcanic-dominated sequences that display somewhat different types of variation in magnetic susceptibility (Figure 19.3).

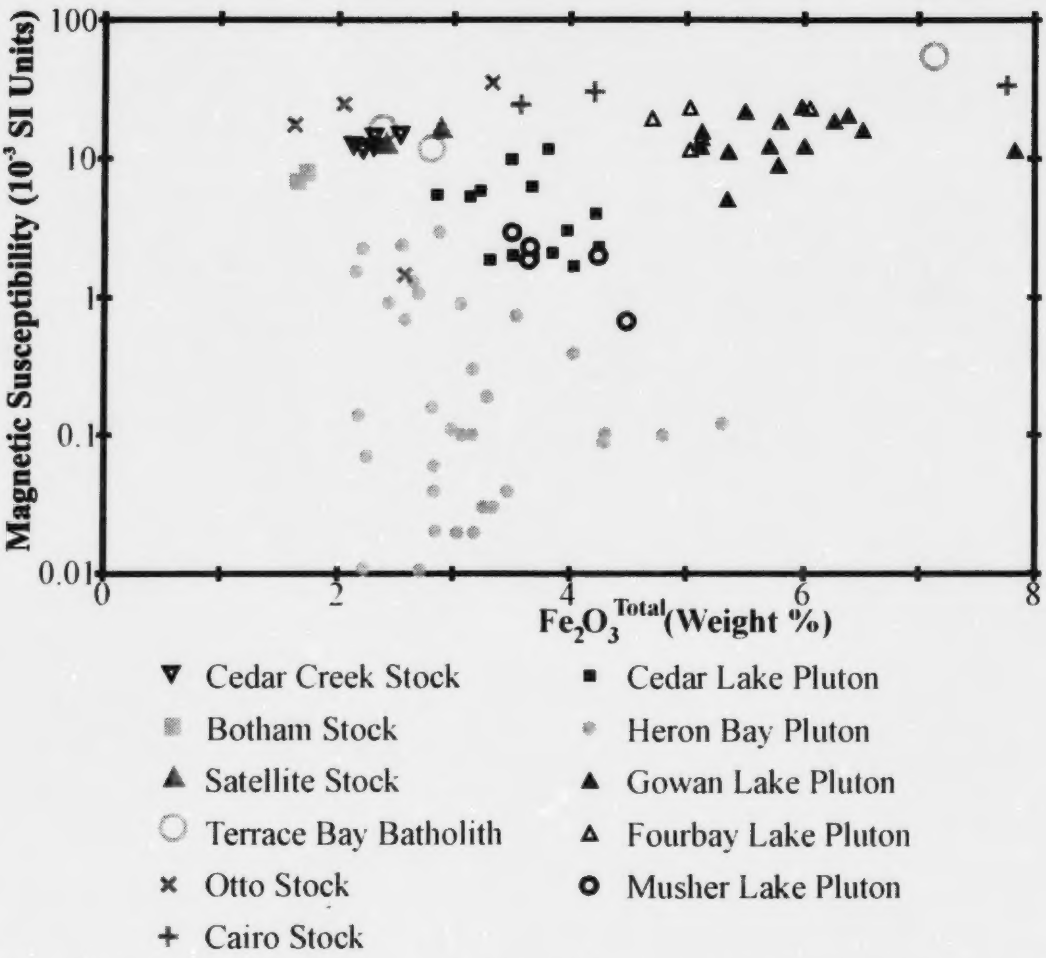
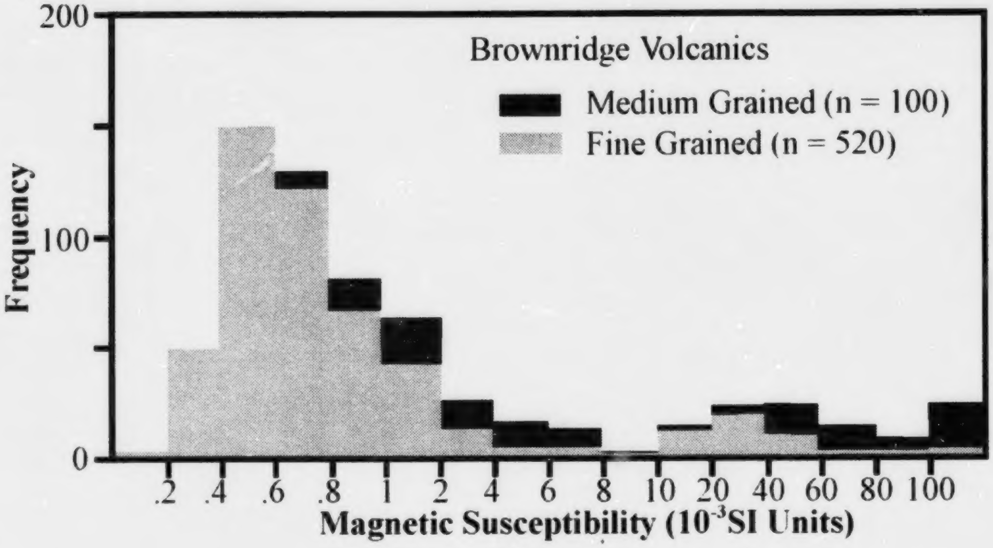


Figure 19.2. Plot of magnetic susceptibility *versus* total iron as Fe_2O_3. Units in the left column of the legend are spatially, and possibly genetically, related to Au ± Mo ± Cu mineralization.

Both sequences display a weakly bimodal frequency distribution of magnetic susceptibility. Within the Brownridge volcanic rocks, the higher susceptibility units are widely distributed through the sequence but are almost without exception massive mafic volcanic units, whereas the lower susceptibility units include both massive and pillowed varieties. Medium-grained units that may represent either thick flows or shallow sills also tend to have higher magnetic susceptibility. These observations suggest that either 1) the higher susceptibility units have not been influenced to the same degree by diagenetic or later alteration processes that significantly modified many of the units or 2) the higher susceptibility units are petrogenetically distinct from the lower susceptibility units. Within the latter hypothesis, the contrasting morphology of the units would arise from different eruptive characteristics (e.g., flow rate, viscosity, etc.) arising from differences in their petrogenesis.



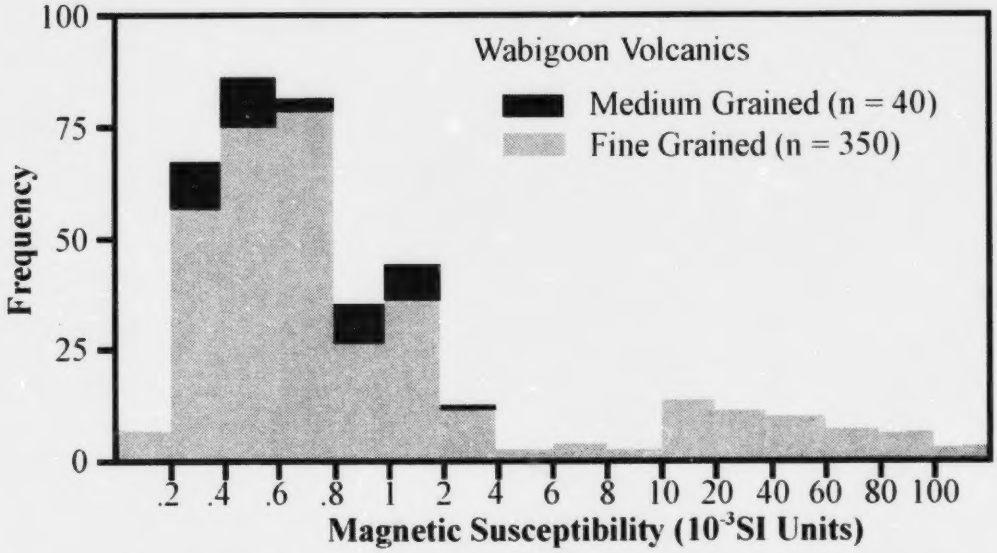


Figure 19.3. Frequency distribution diagrams for magnetic susceptibility in mafic metavolcanic units within the Brownridge and Wabigoon volcanics (Beakhouse, this volume).

The Wabigoon volcanic rocks display a similar bimodal character to their magnetic susceptibilities; however, the variation is primarily related to stratigraphy rather than textural characteristics. Medium-grained units are not abundant in those portions of the Wabigoon volcanic rocks examined to date, but these share the same magnetic susceptibility characteristics as the finer-grained, massive and pillowed varieties with which they are spatially associated. The higher susceptibility units include both massive and pillowed varieties that are restricted to the uppermost portions of the Wabigoon volcanic rocks. In this case, it is most likely that the variation in magnetic susceptibility is reflective of the primary chemical variability of the lavas.

It is probable that secondary alteration processes play a more important role than is the case for intrusive rocks. In particular, the eruptive nature of most of the rocks discussed above makes it less likely that the intrinsic redox state of the primary magmas will be a dominant control. In some cases, the magnetic susceptibility may directly correlate with some chemical variability ($Fe_2O_3^{Total}$, Fe/Mg) in the lava and offer the potential to distinguish different chemical varieties of basalt in the field. The hypotheses discussed above will be further developed and tested as petrographic and geochemical characterization of these sequences becomes available.

Mafic Intrusive Rocks

No systematic investigations of mafic intrusive rocks have been carried out to date; however, there are several obvious applications of magnetic susceptibility to the study of these rocks. In massive- to subtly layered intrusions, this technique may be used to identify variation in oxide mineral abundances that may serve to help define the nature of chemical variability within the pluton and the orientation of subtle layering. Within well-layered intrusions it provides a means to quantify oxide mineral abundances and identify critical intervals in the igneous stratigraphy that record changes in the crystallization of oxide minerals.

A further possible application to mafic intrusive rocks may be the characterization of mafic dike swarms. Measurements on samples from several different dike swarms (Kenora–Fort Frances, Marathon and Matachewan swarms) indicate at least an order of magnitude range in magnetic susceptibility, but further systematic studies would be required to establish whether individual swarms may have characteristic ranges that differ significantly from those of other swarms, and may aid in their distinction.

Alteration

A variety of styles of alteration can lead to the formation or destruction of magnetite. In some cases, the alteration may produce profound mineralogical and textural changes that are readily apparent, whereas in other cases, the alteration may be subtle and difficult to identify without careful, detailed examination. In the latter case, once magnetic susceptibility characteristics and trends in relatively unaltered rocks have been defined, deviations in magnetic susceptibility may provide a means to rapidly identify areas requiring more detailed examination and, in some cases, map the extent of alteration.

A partial list of alteration types that may modify magnetic susceptibility includes:

- Secondary oxidation converting magnetite to hematite resulting in decreased magnetic susceptibility
- Sulphidation reactions resulting in replacement of magnetite by sulphides resulting in decreased magnetic susceptibility
- Exsolution of Fe-Ti oxides accompanying phase transformations in ferromagnesian minerals resulting in increased magnetic susceptibility
- Hydration reactions that, under some circumstances, may produce magnetite from the breakdown of iron-bearing silicates (e.g., serpentinization of olivine) resulting in increased magnetic susceptibility.

Each of these alteration types must be identified and mapped on the basis of petrographic and geochemical criteria. Variation of magnetic susceptibility is a useful tool to rapidly identify anomalous zones that may aid in selection of zones in which these more time-consuming and expensive approaches might be most effectively applied.

Routine Mapping Aid

Geological maps represent a synthesis of observations from individual outcrops. Ideally, these observations are consistently highly reliable but, in practice, this ideal situation is compromised by limitations imposed by poor-quality exposures. In extreme cases (small, glacially polished, lichen-covered outcrops), reliable rock type identification may be extremely difficult.

Systematic measurement of magnetic susceptibility during geological mapping can establish characteristic ranges for major rock types. In some cases, the magnetic susceptibility is sufficiently distinctive that general rock type can be inferred in very poor exposures with some confidence on the basis of the magnetic susceptibility alone. For example, in the Wabigoon area (Beakhouse, this volume) magnetic susceptibilities of magnetite ironstone bearing metasedimentary rocks ($>300 \times 10^{-3}$) and felsic volcanic rocks within the Thunder Lake volcanic rocks ($<0.05 \times 10^{-3}$) do not overlap with the ranges for any other major rock types in the area. More commonly, the magnetic susceptibility of poor exposures is not uniquely diagnostic but may serve to limit the range of possibilities to several rock types characterized by overlapping magnetic susceptibilities. Sharp or gradational transitions in magnetic susceptibility can indicate and delineate geological contacts or alteration zones. Consistent magnetic susceptibilities give some confidence that contacts are not present.

Sampling Control

Magnetic susceptibility is an additional attribute that can be used to assess how representative of an outcrop or unit a particular sample might be. All else being equal, sample locations with magnetic susceptibility that deviate significantly from characteristic ranges for individual outcrops or units may not be representative, and alternative sample selection sites can be selected. Alternatively, specific magnetically anomalous samples might be intentionally selected in order to evaluate the origin of this variation.

In some cases, otherwise apparently uniform units may have bimodal magnetic susceptibility frequency distribution. In these cases, it may be advisable to evaluate other attributes more carefully in order to assess the possibility that the unit is divisible into sub-units that may require multiple sample selection.

Geophysical Modelling

Physical rock property measurements such as magnetic susceptibility can be integrated with ground or airborne potential field surveys to enable the latter to be evaluated more rigorously. Understanding the origin of magnetic anomalies makes it easier to target specific observations to evaluate the significance of regional variations of anomalies on magnetic maps. In simple cases, it may be possible to model the subsurface geometry of features observed on the surface.

SUMMARY

Magnetic susceptibility is a readily acquired, quantitative variable that has many applications to geological mapping as well as more specialized investigations. Magnetic susceptibility is, to a first approximation, a measure of the amount of magnetite in the rock. The abundance of magnetite is a characteristic attribute of a wide range of primary and secondary geological processes, but it is not otherwise readily quantifiable. Magnetic susceptibility provides a means to quantitatively evaluate rock magnetism and select areas where more time-consuming and expensive types of analysis might be most efficiently and effectively employed.

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20. Project Unit 99-001. Precambrian Geology of the Wabigoon Area

G.P. Beakhouse[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

This report presents preliminary interpretations following completion of the first of 5 years of field work focussing on the geology and mineral potential of the Wabigoon area. The field work carried out was primarily focussed on portions of Zealand and Brownridge townships.

The area being investigated lies astride the Wabigoon fault, which has been interpreted to be a major internal structure within the Wabigoon subprovince that separates a northern domain characterized by generally southward-facing, alternating panels of metavolcanic and metasedimentary rocks from a southern domain of generally northward-facing, dominantly volcanic rocks (Beakhouse 1988; Blackburn et al. 1991). Work carried out to date indicates that earlier mapping (Satterly 1941) of the area generally accurately describes the distribution of major lithologic units, although the character of some of these units requires reinterpretation. All of the supracrustal rocks are metamorphosed, and the meta- prefix is subsequently omitted for the sake of brevity and conformity with earlier nomenclature.

GENERAL GEOLOGY

The area north of the Wabigoon fault is characterized by alternating panels of volcanic and sedimentary rocks (Figure 20.1). The nomenclature originally proposed by Satterly (1941) is used informally here to identify the units with the modification that an "arkose" unit occurring within the Thunder Lake sediments is reinterpreted to be a felsic volcanic rock and referred to here as the Thunder Lake volcanics.

Brownridge Sediments

The Brownridge sediments are the northernmost supracrustal unit within the map area. This unit consists primarily of very thinly to medium- (1 to 30 cm) bedded wacke-siltstone. Massive wacke beds up to several metres thick occur locally and are often associated with large rip-up clasts and significant scouring of underlying units. Sedimentary structures (graded bedding, scour, rip-ups and, less commonly, ripple cross-bedding and intraformational conglomerates) are well preserved.

Minor layers and lenses of calc-silicate rock (composed of various combinations of calcic pyroxenes and amphiboles, epidote and carbonate along with plagioclase and quartz) are a widely distributed but minor component of the Brownridge sediments. Many of these are provisionally interpreted to be metamorphosed equivalents of marly sedimentary beds, although a secondary alteration origin cannot be discounted in some cases (*see* discussion *in* "Alteration and Veining"). The calc-silicate layers are

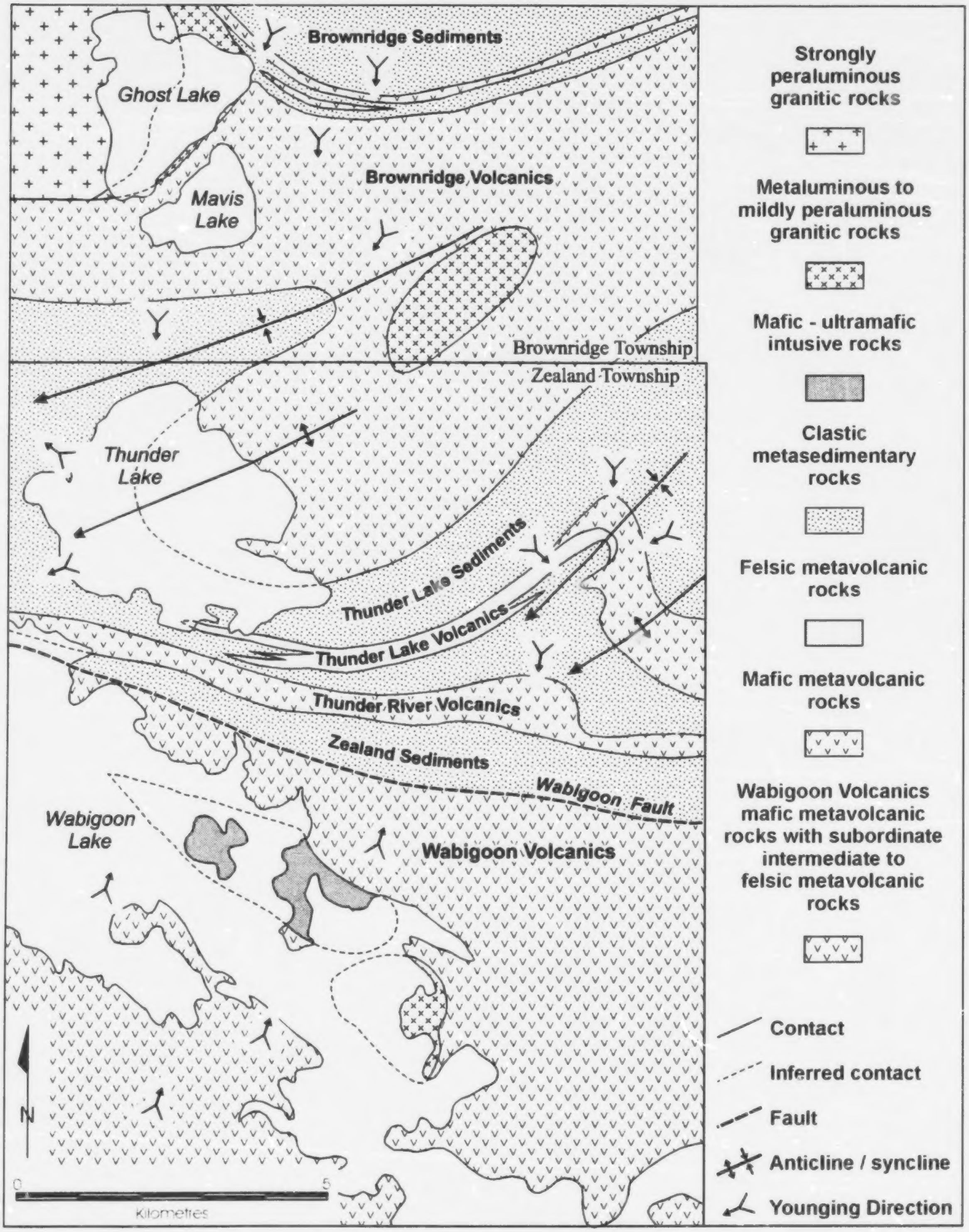

Figure 20.1. Simplified geological map of the Wabigoon area.

commonly boudinaged and some of the lenses are simply disrupted layers, although some appear to be isolated and may represent original concretions.

Abundant facing indicators observed in a well-exposed (clear-cut logging) area east of Ghost Lake overwhelmingly indicate that the unit youngs to the south. Several thin mafic volcanic units are interlayered with the Brownridge sediments near the top of the unit. Several contacts between the sedimentary rocks and interlayered volcanic rocks have been observed, and they appear to be conformable with minimal strain and no indication of shearing. Further investigations are planned to address the nature of the Brownridge sediments–Brownridge volcanics contact, as well as the relationship between the volcanic rocks occurring in the Brownridge sediments and those of the Brownridge volcanics.

Brownridge Volcanics

Only the western portion of the Brownridge volcanics within the map area was investigated this year. That portion of the Brownridge volcanics examined to date consists of massive and pillowed mafic flows together with medium-grained, gabbroic rocks that may represent either intrusions or thick flows. Thin felsic units previously identified in the area south and southeast of Mavis Lake (Satterly 1941) are provisionally reinterpreted to be variolitic basalts. These rocks are generally aphyric although mafic phenocrysts were identified in a small percentage of outcrops. It is not clear if these porphyritic varieties may be related to amphibole-phyric, calc-alkaline, intermediate to felsic volcanic rocks identified to the east in Laval township (Berger 1990).

Limited new observations of facing direction are consistent with the interpretation of Satterly (1941) that the Brownridge volcanics young generally to the south.

Thunder Lake Sediments

The Thunder Lake sediments include two separate panels of rock separated along a portion of their strike length by the Thunder Lake volcanics. Thin- to medium-bedded wacke-siltstone characterized by even, continuous bedding is the predominant component in both panels. Thin magnetite ironstone layers are a conspicuous minor component within the Thunder Lake sediments north of the Thunder Lake volcanics but are rare within the southern panel. Minor, thin garnet-rich (<70% garnet) and calc-silicate layers may represent original more pelitic and marly layers, respectively. In one location, the calc-silicate material forms discordant veins, and suggests that some of this material is remobilized or originated by secondary alteration processes. The garnet-rich layers are often closely spatially associated with the ironstone layers.

A limited number of determinations indicate that tops, although locally reversed by tight to isoclinal minor folding, are generally to the south in both the north and south panels. Contact relations with the Brownridge volcanics have not been observed but the data are permissive of a conformable stratigraphic relationship. The contacts with the Thunder Lake volcanics appear to also be conformable although these are commonly moderately highly strained and a loci of abundant quartz veining.

Thunder Lake Volcanics

The term Thunder Lake volcanics is informally introduced here to refer to a dominantly felsic volcanic unit within the Thunder Lake sediments that was formerly interpreted to be an arkose (Satterly 1941). The felsic units are conformably interlayered with wacke-siltstone of the Thunder Lake sediments. Lenses of sedimentary rock occurring with the felsic unit are similar to those elsewhere in the Thunder Lake sediments.

The felsic unit is characterized by quartz and feldspar crystals in a finer-grained felsic matrix. The quartz phenocrysts are rounded, 1 to 3 mm crystals, whereas the feldspar crystals are more angular and slightly smaller, although their preservation is highly variable and generally poor as a result of secondary alteration. Locally, texturally diverse felsic lithic lapilli constitute up to 25% of the rock. Small, tabular, darker fragments are provisionally interpreted to be flattened pumice fragments. Subtle bedding is apparent locally but much of the unit is massive. The felsic rocks are interpreted to be felsic tuffaceous unit conformably interlayered with the Thunder Lake sediments.

The relationship of the felsic volcanic rocks with minor massive and pillowed mafic flows associated with the eastern and western terminations of the felsic unit is not known.

Thunder River Volcanics

The Thunder River volcanics (Satterly 1941) consist of massive and pillowed mafic flows together with medium-grained gabbroic rocks that are possibly closely related (thick flows or sub-volcanic sills). Minor amounts of melagabbro to peridotite occur locally along the northern margin of the unit.

Zealand Sediments

The Zealand sediments consist of very thin- to medium-bedded wacke-siltstone. Many exposures of this unit, particularly those near both the northern and southern contacts, are highly strained and consequently the primary characteristics of this unit are not well constrained.

Wabigoon Volcanics

The Wabigoon volcanics are an extensive unit, extending well beyond the map area, that is dominated by mafic metavolcanic rocks (Blackburn et al. 1991). Preliminary observations within the upper half of the Wabigoon volcanics in the Wabigoon Lake area confirm the dominance of massive and pillowed mafic flows. Minor amounts of intermediate to felsic lapilli-tuff and tuff are locally interlayered with the mafic volcanic rocks. Very fine-grained, glassy felsic volcanic rock with a distinctive concoidal fracture that may be a flow was observed at one locality.

The limited portion of the Wabigoon volcanics examined to date is, with the exception of exposures near the Wabigoon fault, characterized by low degrees of strain and good preservation of primary structures. All top determinations indicate the Wabigoon volcanics young to the north.

Intrusive Rocks

Most of the medium to coarse-grained mafic igneous rocks in the map area have been deformed along with mafic volcanic rocks with which they are closely spatially associated. These rocks are most reasonably interpreted to be syn-volcanic sills or thick ponded flows and have been alluded to in the preceding sections. The only possible exception to this generalization is a moderately large (~5 km long by 1 km wide) sill-like body of gabbroic to ultramafic composition near the top of the Wabigoon volcanics. A syn-volcanic origin cannot be ruled out but the texture and general character of the unit are atypical of medium-grained mafic igneous rocks occurring elsewhere in the map area.

Felsic intrusive rocks are broadly subdivided into metaluminous to weakly peraluminous granodiorite to tonalite characterized by the presence of biotite and/or hornblende and strongly peraluminous granite to tonalite characterized by the presence of muscovite ± biotite ± garnet ± tourmaline. The strongly peraluminous variety are restricted to the northern part of the map area and are part of, or related to, the Ghost Lake batholith, which is interpreted to be parental to rare metal pegmatites in the Dryden area (Breaks 1989).

STRUCTURAL GEOLOGY

The areas north and south of the Wabigoon fault have markedly different deformational styles. South of the Wabigoon fault, the dominantly volcanic sequence is a northward younging homocline but penetrative fabrics are sporadically and weakly developed. Primary form of pillows and other primary structures is well preserved in horizontal sections although there is currently little constraint on the extent of possible vertical stretching.

The area north of the Wabigoon fault is characterized by alternating volcanic or sedimentary dominated units that are generally southward facing and has heterogeneous, weakly to strongly developed penetrative fabrics. An earlier (D_1), ubiquitous, weakly to strongly developed fabric is parallel to bedding with the exception of one outcrop where it is interpreted to be parallel to the axial surface of rootless, tight to isoclinal folds. The D_1 fabric development heterogeneity is, in part, controlled by primary lithological characteristics (e.g., fabric in mafic volcanic sequences is better developed in interflow hyaloclastite/breccia units than massive, fine- to medium-grained units). The D_1 fabric, along with bedding, is deformed on a variety of scales into southwesterly plunging (D_2) folds having Z-asymmetry. These regional scale folds, as well as the contrasting characteristics to the south of the Wabigoon fault, are readily apparent on regional aeromagnetic maps (Figure 20.2). On a detailed scale, most outcrops having suitable markers or well developed D_1 fabrics display Z-asymmetric minor folds that commonly have a D_2 fabric (spaced cleavage to pervasive penetrative schistosity) developed parallel to the axial surface of the minor folds.

ALTERATION AND VEINING

A variety of styles and varieties of alteration are recognized in the field. Secondary hydration reactions producing chlorite, white mica and epidote are heterogeneously developed with more highly strained rocks typically being more intensely altered. The nature of the alteration mineralogy is primarily a function of rock type (e.g., chlorite in mafic rocks, white mica in felsic rocks) although further investigations are required in order to assess the extent to which this alteration has been non-isochemical.

Anomalous garnet abundance (< 70%) in selected layers within the Thunder Lake metasediments, especially associated with magnetite ironstone layers, may either reflect alteration or isochemical metamorphism of pelitic layers. Abundant, large garnet crystals also occur in the selvages of pillows at one location within the Thunder River volcanics.

Calc-silicate mineral assemblages occur in a variety of rock types. Those occurring in metasedimentary rocks may reflect near isochemical metamorphism of original marly beds although several examples of discordant calc-silicate veins were noted in the Thunder Lake and Brownridge sediments. Calc-silicate rocks occurring in mafic volcanic sequences are closely associated with pillowed and pillow-breccia units and may reflect early diagenetic seafloor alteration. Epidote-filled fractures and

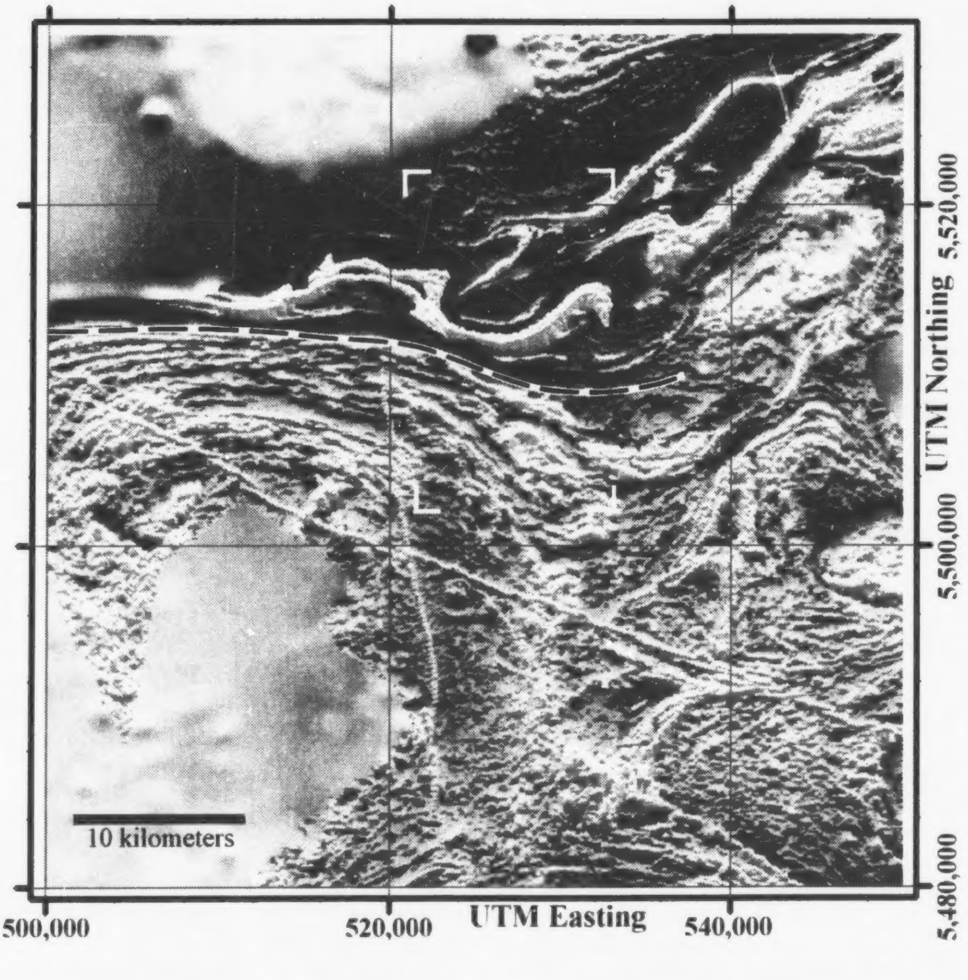

Figure 20.2. Shaded, total field magnetic image of the Wabigoon area. The corner tick marks approximate area of the preceeding figure. The dashed line indicates the approximate position of the Wabigoon fault. The northwestern and southwestern portions of the image, corresponding to dominantly granitoid areas, are infilled with lower-resolution magnetic data.

actinolite veins as well as more diffuse calc-silicate alteration also occur locally within felsic volcanic rocks of the Thunder Lake volcanics.

Tourmaline is a common, and locally abundant mineral within units lying to the north of the Wabigoon fault and particularly in the Brownridge sediments. It occurs as irregular, discordant veins along which there may be selective, near-complete replacement of specific layers. It is also associated with quartz veins and strongly peraluminous granitic dikes. This alteration is locally observed to overprint D_2 deformational structures and is interpreted to be a very late alteration.

Quartz veining is widespread and locally abundant. Tourmaline is locally associated with quartz veining, especially to the north of the Wabigoon fault. Iron-carbonate is associated with some of the quartz veins occurring to the south of the Wabigoon fault. Quartz veins are especially abundant near the contacts between metasedimentary rocks and the felsic volcanic component of the Thunder Lake volcanics. Relatively older quartz veins in this area are deformed by D_2 folds whereas a younger generation occupies tension gashes oriented subparallel to the axial surface of D_2 folds, suggesting that they post-date this deformational event.

MINERALIZATION

A wide variety of styles of mineralization occur, or are potentially present, in the Wabigoon area. North of the Wabigoon fault, interest has recently focussed on gold associated with the felsic volcanic component of the Thunder Lake volcanics where Corona Gold Corporation has outlined a drill-indicated resource of 3.78 million tonnes averaging 7.02 g/t Au (853 000 ounces Au) (Hinz et al. 2000). Some of the noteworthy characteristics of this mineralization that may be relevant to exploration for similar deposits include 1) association with felsic metavolcanic unit within a dominantly metasedimentary domain, 2) association with disseminated sulphide mineralization, 3) area of heterogeneous, moderately high strain, 4) widespread Z-asymmetric folding on a variety of scales, 5) occurrence within a large-scale compressional flexure of the regional fabric and 6) post-ore extension (post-D_2 quartz filled tension gashes). The general setting of the Thunder Lake gold occurrence is similar in some respects to that of the Hemlo gold deposit (Muir 1997; Beakhouse, in press). There is potential for the discovery of similar deposits in metasedimentary-dominated belts throughout the Superior Province, including those extending from the Wabigoon area into the Sioux Lookout area to the northeast and eastern Lake of the Woods area to the southwest.

There is also potential for gold mineralization associated with quartz veins and shear zones. These are commonly associated with lithological contacts. Possible stratigraphic control has also been proposed for gold mineralization occurring in the Wabigoon volcanics (Parker 1989).

Rare element mineralization is associated with pegmatites related to the strongly peraluminous Ghost Lake batholith (Breaks 1989) and there is potential for the discovery of additional occurrences of this style of mineralization, primarily within the Brownridge volcanics and Brownridge sediments.

The Wabigoon volcanics are interpreted to be the most prospective unit for VMS-style base metal mineralization. Regional reconnaissance investigations in preparation for this project identified an F3 rhyolite ($Zr = 759$ ppm; $Y = 127$ ppm; $Yb_N = 88$; $La_N/Yb_N = 3.56$) within the Wabigoon volcanics on Eagle Lake to the west of the map area.

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21. Project Unit 99-022. The Entwine Lake Intrusion: A Neoarchean Cu-Ni-PGE Bearing Intermediate to Mafic Complex in the Western Wabigoon Subprovince, Northwestern Ontario

J. Arnold[1], G. Beakhouse[2], R. James[3]

[1]Geology Department, Laurentian University
[2]Precambrian Geoscience Section, Ontario Geological Survey
[3]Geology Department, Laurentian University

INTRODUCTION

The Entwine Lake intrusion, hereafter referred to as the ELI, is an east-trending, tadpole-shaped, Neoarchean intrusion located 90 km south of Dryden, Ontario. The ELI is approximately 35 km long with a near-circular, 10 km diameter western portion with a narrow tail extending to the east (Stone and Hallé 1999). Access is provided to the intrusion through the use of secondary logging roads off Highway 502 in the north and from Entwine Lake in the south.

The pluton has recently attracted attention due to Ni-Cu-PGE mineralization located in the northern portion of the intrusion by Champion Bear Resources. The association with PGE mineralization is of particular interest as this intrusion has characteristics similar to that of a suite of mantle-derived monzodioritic intrusions (termed sanukitoid by Stern, Hanson and Shirey 1989) that have not previously been examined for their PGE potential.

The project is a joint OGS/LU mapping school M.Sc. thesis project designed to map the ELI at a scale of 1:20 000 and further our understanding of the nature and origin of the pluton and its contained mineralization. This report presents preliminary results from the first field season.

REGIONAL GEOLOGY

The Entwine Lake intrusion occurs within the Wabigoon Subprovince. Previous regional-scale mapping indicates that the intrusion was emplaced into foliated to gneissic, granitic to tonalitic intrusive rocks and minor mafic metavolcanic rocks (Stone and Hallé 1999). One such metavolcanic unit, having an average width of 100 m, occurs at the contact of the intrusion, and has been traced nearly continuously around the ELI (Figure 21.1). The ELI occurs within the core of a regional-scale synclinal fold of the metavolcanic septa and the regional gneissosity (Stone and Hallé 1999). The depth of emplacement is interpreted to be 9 to 12 km based on aluminum-in-hornblende geobarometry (Stone and Hallé 1999). Anisotropy of magnetic susceptibility suggests that the distinctive shape of the pluton is due in part to syn-emplacement ballooning of its western portion (Arnold and Benn 2000).

ENTWINE LAKE INTRUSION

The ELI has been subdivided into four main units based on chronological, structural and mineralogical relationships. These units range from biotite monzodiorites to quartz diorites and amphibole-augite diorite/gabbros. Age relationships between these units have been established based on structural evidence and crosscutting relations. These four units, listed from oldest to youngest, as well as a wide-spread, volumetrically minor, pyroxenitic phase and minor granitic dikes are described in further detail below.

Foliated Monzonite/Monzodiorite

The oldest unit occurring primarily within the eastern tail of the ELI consists of foliated monzonite to monzodiorite, with subordinate quartz monzonite to quartz monzodiorite. Mafic mineralogy includes biotite, clinopyroxene and amphibole, and has a colour index of 20 to 25. Sulphide minerals are not observed. This unit is primarily equigranular with local development of incipient potassium feldspar

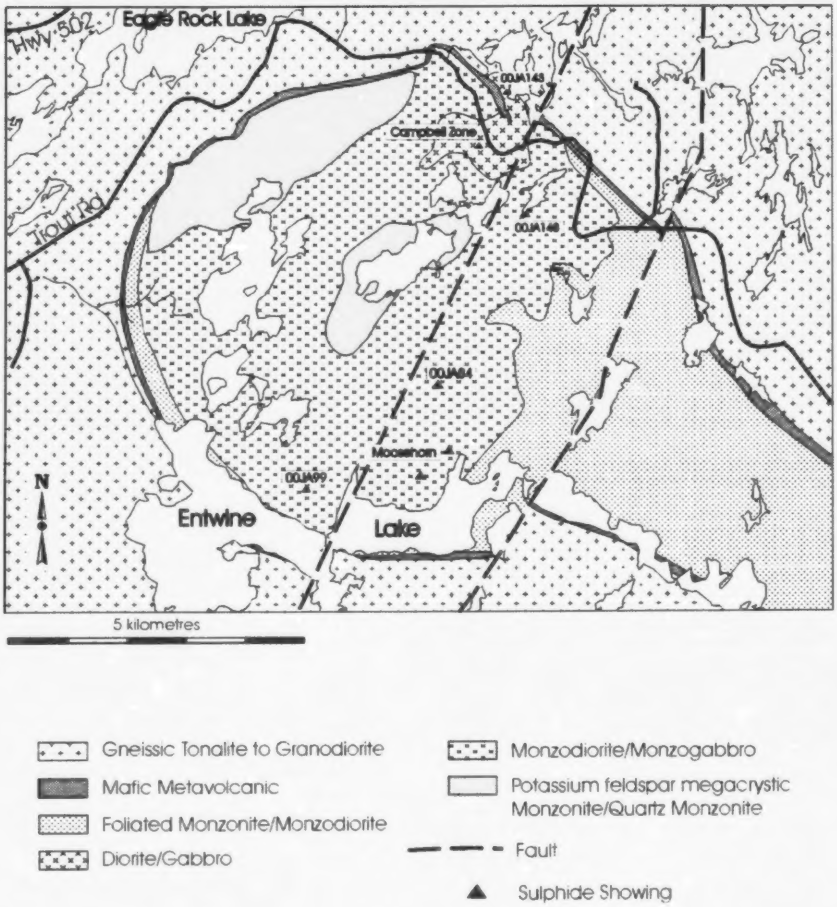

Figure 21.1. Generalized geological map of the Entwine Lake intrusion.

megacrystic textures. A distinctive feature of this unit, relative to other phases, is the presence of a weakly to moderately well developed fabric defined by mafic mineral alignment and, to a lesser extent, enclave alignment. The intensity of the fabric development in this phase is much less than that of the adjacent country rocks and may be related to magmatic flow.

Diorite/Gabbro

The next youngest unit is a diorite, which locally grades into quartz diorite, and gabbro. Clinopyroxene and amphibole are the predominant mafic minerals with orthopyroxene occurring in the fresh gabbroic phases. Biotite occurs as a minor component. The colour index of this unit is 25 to 30. This unit is coarse grained, equigranular and ranges from weakly to strongly altered. Secondary mineralogy includes saussuritized plagioclase with interstitial mineral assemblages consisting of actinolite, chlorite, epidote and some carbonate (Stone 2000). Zones of 5 to 10% Ni-Cu sulphide disseminations are observed in this phase and are interpreted to be of primary magmatic origin. The platinum group element–enriched mineralization in the Campbell zone also contains Pd-Bi tellurides and electrum associated with these greenschist mineral assemblages (Stone 2000).

Monzodiorite/Monzogabbro

The bulk of the lobate western end of the ELI consists of a biotite-rich monzodiorite/monzogabbro unit, which grades into quartz diorite. Mafic mineralogy includes abundant biotite, amphibole and pyroxene. The colour index is 25 to 30 and locally as high as 40. No obvious secondary mineralogy was observed. This unit is medium grained, equigranular, texturally massive, and locally develops magmatic flow alignments of the mafic minerals. The quartz dioritic members host up to 5% chalcopyrite, pyrrhotite, pyrite and magnetite. PGE content of these rocks is unknown. Mafic segregations are common and are interpreted to be co-mingled mafic magmas.

K-Feldspar Megacrystic Monzonite/Quartz Monzonite

A potassium feldspar megacrystic monzonite to quartz monzonite crosscuts units described above and is interpreted to be the youngest major phase within the ELI. Two distinct bodies of this unit are observed at the core and the western margin of the ELI (Figure 21.1). Mafic mineralogy in this unit includes amphibole, biotite and clinopyroxene and typically has a colour index of 15 to 20. Sulphide minerals are not observed in this unit. A distinctive feature of this unit is the presence of ubiquitous potassium feldspar megacrysts. Preliminary analysis of these feldspars suggests they are a late magmatic phase, as they often host inclusions of fine-grained plagioclase and amphibole. Locally this unit shows mafic mineral alignment as well as megacryst alignment due to magmatic flow.

Pyroxenite

Inclusions of pyroxene gabbro and pyroxenite, on average 50 to 100 m in diameter, are observed in all previously described units of the ELI. The inclusions are deep green, coarse grained, and often the pyroxenes have been altered to micas. They show a pegmatitic phase of coarse green amphiboles, sometimes cored by plagioclase in a coarse plagioclase matrix. The pegmatitic pods are generally ovoid pods 15 to 25 cm in length, half that in width. This phase hosts 1 to 2% disseminated pyrite and potential PGE mineralization.

Late Granitic Dikes

Aplitic and quartz pegmatitic dikes are observed to cut all phases of the Entwine stock, and strike a consistent northeast-southwest direction. The similar orientation of these dikes with two shear zones suggests that shearing played a role in controlling the emplacement of the dikes.

FAULTS

Two regional northeast-striking brittle faults are manifest by offset of the contact of the pluton and mafic metavolcanic. No brittle faulting has been recognized within the pluton but hematite alteration observed in outcrop and aeromagnetic data outline these structures.

SULPHIDE AND PGE MINERALIZATION

Past mineral exploration has led to the identification of a number of Ni-Cu sulphide occurrences within the ELI. Additional occurrences have been identified during the course of this field work (Table 21.1). Exploration carried out by Champion Bear Resources Ltd has identified platinum group element–enrichment within one of these occurrences (Campbell zone). Stone (2000) reports an average grade of 1.0 g/t combined Au, Pt and Pd, 3.8 g/t Ag and 0.5% Cu and Ni. Field observations indicate that sulphide mineralization is widespread in the diorite/gabbro and monzodiorite/monzogabbro phases. No significant sulphide occurrences were outlined in the foliated monzonite nor the potassium feldspar megacrystic monzonite phases of the ELI. Sulphide minerals identified include chalcopyrite, pyrrhotite, pyrite and locally bornite and malachite. Nickel- and copper-bearing sulphides occur as disseminations typical of those occurring in magmatic sulphide deposits. The only known platinum group element–enriched zone, the Campbell zone, contains Pd-Bi tellurides and electrum associated with greenschist facies metamorphic mineral assemblages such as epidote, chlorite, actinolite and minor carbonate. Further work is planned to establish background PGE abundances of the various components of the ELI as well as the mineralogy and Ni-Cu-PGE tenor of all the occurrences.

Table 21.1. Locations of sulphide mineralization within the ELI.

Sample Number	Location (UTM**)	Description
Moosehorn Showing (00JA86)	524874, 5444816	Med gr. monzodiorite (5% cp, py, po)
00JA84*	525539, 5446198	Med.gr. monzodiorite (2% py, cp)
00JA99*	522639, 5444133	Med – coarse gr. monzodiorite (2% py, cp, po)
00JA101*	523326, 5444194	Coarse gr. diorite (2% py, cp, po)
00JA121*	522391, 5445113	Med – coarse gr. gabbro (2% py, cp)
00JA143*	526165, 5451009	Coarse gr. quartz diorite (2% py, cp)
00JA148 (old trench)	526455, 5448973	Med – coarse gr. monzodiorite (5% cp, py, po, malachite)
Campbell Zone (00JA166)	525438, 5450454	Coarse gr. diorite (5% cp, py, po, bn)

* new showing; ** UTM coordinates presented as "easting, northing".
Abbreviations: bn, bornite; cp, chalcopyrite; gr, grained; po, pyrrhotite; py, pyrite.

CONCLUSIONS

Preliminary work done on the ELI in the summer of 2000 has shown that it consists of four distinct major lithological units ranging in composition from quartz monzonite to gabbro. Contacts between the various units are highly gradational suggesting that near continuous magma pulses were emplaced to form the western lobe of the igneous complex. Most of the notable sulphide occurrences have been located within the diorite/gabbro and monzodiorite/monzogabbro phases of the intrusion and are perceived to be the most prospective units of the pluton for any PGE mineralization. Sulphide mineralogy is characteristically 5 to 10% chalcopyrite, pyrite and pyrrhotite. Focus of subsequent investigation includes:

1. Petrology and petrogenesis of the intrusion
2. Evaluation of the roles of magmatic *versus* hydrothermal processes controlling the sulphide mineralization, and particularly the PGE distribution.

The results reported for the ELI suggest that further work is warranted to test the potential for similar mineralization in monzodioritic intrusions elsewhere in the Superior Province.

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22. Project Unit 98-002. Gold Mineralization and Wall Rock Alteration in the Red Lake Greenstone Belt: A Regional Perspective

J.R. Parker[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

This report summarizes preliminary observations and interpretations from the first year of a multi-year project conducted in conjunction with the Western Superior NATMAP program. The project was initiated to study gold mineralization and related hydrothermal alteration at a regional scale within the Red Lake greenstone belt. This year, the majority of fieldwork focussed on supracrustal rocks in the eastern and middle portions of the greenstone belt.

The purpose of this work is to 1) identify new gold exploration targets; and 2) attempt to constrain the timing of gold mineralization and hydrothermal alteration relative to deformation and metamorphism by:

- documenting and cataloguing the characteristics and regional distribution of hydrothermal alteration including structural and lithologic controls and geochemical and mineralogical attributes;
- characterizing and comparing gold mineralization and related hydrothermal alteration in early Mesoarchean (pre-2745 Ma) and late Neoarchean (2745 to 2700 Ma) metavolcanic assemblages;
- examining the possible role of the various intrusive rocks within the greenstone belt by documenting their petrology, mineralogy and geochemical characteristics; structural characteristics; distribution and mineralogical features of contact metamorphic aureoles.

Unless otherwise noted, all data for geochemical analyses presented in this report were provided by the Geoscience Laboratories, Ontario Geoservices Centre in Sudbury.

BACKGROUND

The Red Lake greenstone belt is an important gold camp that has produced approximately 18.4 million ounces of gold from 1930 to the end of 1999. Two mines are currently in production: the Placer Dome North America–Campbell mine which has been in continuous production since 1949; and the Goldcorp Inc.–Red Lake mine (Figure 22.1). The Red Lake gold camp is famous for very high grade gold mineralization such as the High Grade Zone at the Goldcorp mine where diamond drill intersections of 17.46 ounces gold per ton across 16.4 feet have been reported (Hinz et al. 2000). The gold deposits at Red Lake are similar to quartz-carbonate vein deposits (Robert 1995) associated with deformation and folding in metamorphosed volcanic, sedimentary and granitoid rocks. Deposits at the Campbell and Goldcorp mines may represent shallow-level Archean lode-gold deposits which Gebre-Mariam, Hagemann and Groves (1995) suggest are upper crustal equivalents to deeper "mesothermal" deposits. The past-producing Madsen gold deposit, however, is interpreted by Dubé et al. (2000) as a high temperature

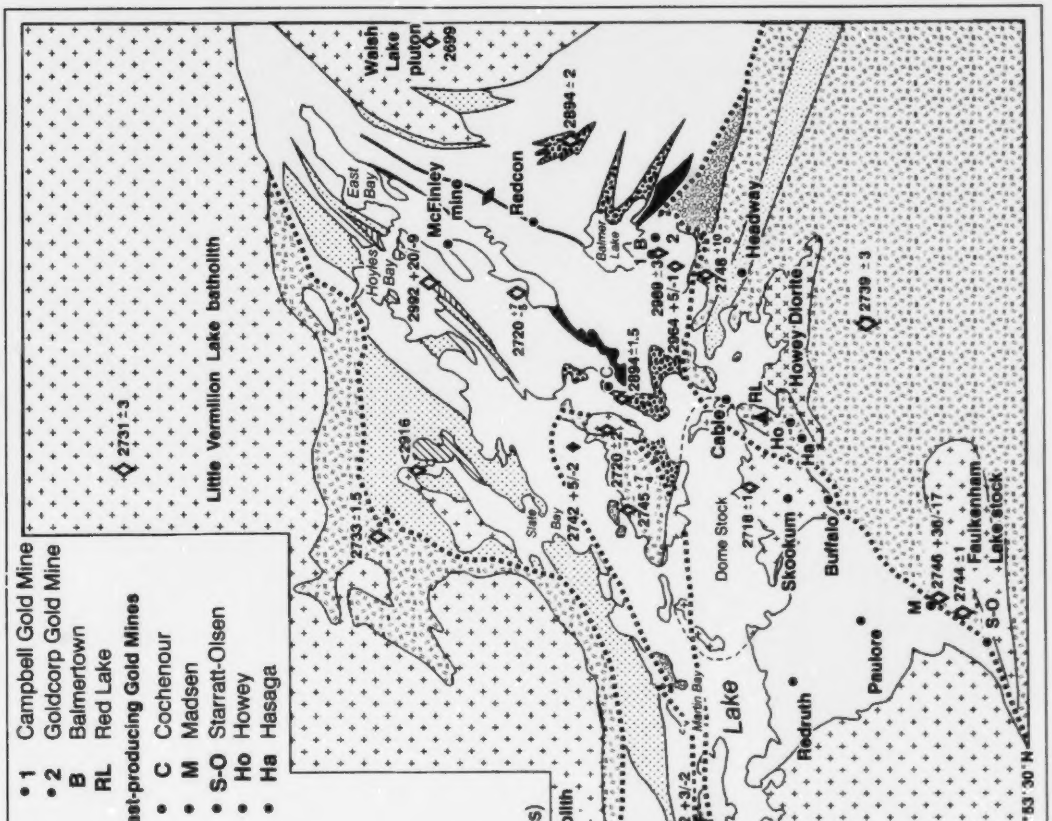

Figure 22.1. General geology of the Red Lake greenstone belt; distribution of supracrustal assemblages; and location of producing gold mines and some past-producing gold mines. Locations referred to in the text are indicated on the figure (modified after Sanborn-Barrie, Skulski and Parker in press).

gold deposit similar to gold skarns in mafic metavolcanic rocks (Mueller and Groves 1991). The Madsen deposit can be classified as "hypozonal" and may have formed at temperatures and pressures in the range 400 to 650°C and 3 to 5 kbar (>12 km), respectively (Gebre-Mariam, Hagemann and Groves 1995).

The Red Lake greenstone belt comprises 6 distinct supracrustal assemblages (*see* Figure 22.1)—deposited over a span of about 300 million years—affected by regional polyphase deformation, multiple metamorphic events and 3 episodes of granitoid emplacement. Table 22.1 summarizes the lithologies in each assemblage and some of the radiometric ages that have been reported. The greenstone belt is dominated by 4 Mesoarchean metavolcanic assemblages (*see* Figure 22.1): Balmer, Ball, Trout Bay and Bruce Channel. Clastic rocks of the Slate Bay assemblage have a maximum depositional age of 2916 Ma (Corfu et al. 1998) and may be Mesoarchean (Sanborn-Barrie et al. 2000). Neoarchean metavolcanic rocks of the Confederation assemblage (2750 to 2730 Ma) (Stott and Corfu 1991) occur along the northeast and southeast flanks of the greenstone belt. The Red Lake belt has been previously described (Stott and Corfu 1991) as a collage of allochthonous assemblages juxtaposed along fault boundaries within larger deformation zones (Andrews et al. 1986). However, Sanborn-Barrie et al. (2000) have recently identified a major unconformity between the Mesoarchean Balmer assemblage and the Neoarchean Confederation assemblage which suggests that Confederation assemblage rocks were erupted and deposited on Mesoarchean crust. Similar observations have been made in the Birch–Uchi greenstone belt situated east of Red Lake (Rogers et al. 2000).

The majority of significant gold deposits occur within the Mesoarchean Balmer assemblage. The assemblage consists of pillowed, tholeiitic, basalt flows, basaltic komatiite and spinifex-textured komatiite flows interlayered with minor clastic metasedimentary rocks and chert-magnetite iron formation. The assemblage also contains minor units of massive, aphanitic felsic rocks with rare primary textures. These rocks are commonly fault-bounded and have been mapped as extrusive rhyolite (Pirie and Grant 1978a), however, discordant contact relationships suggest that some felsic units may be intrusive. The author has also recognized that several lithologies previously mapped as intermediate to felsic metavolcanic rocks—in Baird (Wallace and Atkinson 1993), Fairlie (Riley 1978) and Dome (Ferguson 1965; Atkinson 1994) townships—are intensely altered mafic and ultramafic rocks. In fact, the only convincing intermediate to felsic, extrusive metavolcanic rocks are local units of coarse tuff breccia on the south shore of Coin Lake in Baird Township and at Hoyles Bay on Red Lake. The Balmer assemblage is intruded by gabbroic to peridotitic intrusive rocks; Confederation-age felsic intrusive rocks; a variety of late mafic, intermediate and felsic dikes; the south lobe of the Dome stock; the Killala–Baird batholith and Walsh Lake pluton (*see* Figure 22.1).

Sanborn-Barrie et al. (2000) have recognized 2 main stages (D_1 and D_2) of regional, penetrative, ductile deformation in the greenstone belt. D_1 is a north-striking foliation that is axial planar to F_1 folds whereas D_2 is an easterly-striking foliation that overprints D_1 and is axial planar to D_2 folds that refold F_1 folds (Sanborn-Barrie et al. 2000). Menard and Pattison (1998) correlated D_1 with the intrusion of the Douglas Lake pluton and the Little Vermilion Lake batholith at 2734 ± 2 Ma (Corfu and Stone 1998) and 2731 ± 3 Ma (Corfu and Andrews 1987), respectively. D_2 is a complex deformation associated with upright folding and emplacement of granitoid batholiths at about 2720 Ma (Dome stock, McKenzie Island stock, Hammell Lake pluton). A third phase of granitoid emplacement is represented by the Killala–Baird batholith at 2704 ±1.5 Ma (Corfu and Andrews 1987) and the Walsh Lake pluton (also known as the Cat Island pluton) at 2699 Ma (Noble 1989). Granitoid emplacement at ca. 2720 Ma corresponds with the "Uchian phase" of the Kenoran orogeny (2713 to 2701 Ma; Stott et al. 1989), and the D_2 deformation event, whereas granitoid emplacement at ca. 2700 Ma appears to be posttectonic (M. Sanborn-Barrie, GSC, personal communication, 2000). Table 22.1 summarizes the characteristics of the major intrusions in the belt and their radiometric ages.

Table 22.1. Summary of lithologies and radiometric ages for supracrustal assemblages and major granitoid intrusions in the Red Lake greenstone belt.

Supracrustal assemblage	**U-Pb Age (Ma)**	**Rock types and descriptions****	**References**
Confederation (southeast Red Lake)	2748 +10/-5 to 2739 ± 3	Basal sequence is commonly tholeiitic to calc-alkaline with lobe-hyaloclastite rhyolite flows; intermediate pyroclastic rocks; basalt; and feldspar-phyric andesite. Calc-alkaline rocks are more abundant at higher stratigraphic levels.	Corfu and Wallace 1986
Confederation (north Red Lake)	2733 ± 1.5	Strongly calc-alkaline pyroclastic rocks.	
Trout Bay	2853 ± 2	Fine-grained clastic metasedimentary rocks (wacke, argillite) interlayered with subordinate intermediate pyroclastic rocks and chert-magnetite iron formation. Overlain by tholeiitic, pillowed basalts.	T. Skulski, GSC, pers. comm., 2000
Bruce Channel	2894 ± 1.5; 2894 ± 2	Strongly calc-alkaline intermediate pyroclastic rocks overlain by pebble conglomerate, thinly bedded wacke and capped by chert-magnetite iron formation.	Corfu and Wallace 1986; Corfu and Andrews 1987
Slate Bay	2916	Interlayered, feldspathic wacke, lithic wacke and argillite; lenses of pebble and cobble conglomerates and quartz-rich pebble conglomerate and quartz arenite.	Corfu et al. 1998
Ball	2940 ± 2; 2925 ± 3	Typically calc-alkaline intermediate pyroclastic rocks and rhyolite flows; komatiitic to tholeiitic basalt; overlain by chert-magnetite iron formation and dolomitic marble which contains stromatolites.	Corfu and Wallace 1986
Balmer	2992 +20/-9; 2989 ± 3; 2964 +5/-1	Tholeiitic basalt, basaltic komatiite and komatiite interlayered with subordinate chert-magnetite iron formation; minor clastic metasedimentary rocks; minor intermediate to felsic pyroclastic rocks; and rhyolite.	Corfu and Andrews 1987
INTRUSIVE ROCKS			
Walsh Lake pluton	2699	Potassium feldspar- and quartz-phyric monzogranite; xenolith-rich, diorite or granodiorite; possible oxidized phase at Ranger Lake with broad magnetic anomaly.	Noble 1989
Killala–Baird batholith	2704 ± 1.5	Potassium feldspar- and quartz-phyric monzogranite; xenolith-rich, diorite or granodiorite; oxidized, magnetite-bearing marginal phase.	Corfu and Andrews 1987
Hammell L. batholith	2717 ± 2	Potassium feldspar and quartz porphyritic monzogranite; associated anorthositic intrusion.	McMaster 1987
Dome stock	2718 ± 1	Granodiorite and augite porphyritic diorite/gabbro	Corfu and Andrews 1987
McKenzie stock	2720 ± 2	Augite porphyritic diorite-gabbro; some ultramafic rocks; granodiorite	Corfu and Andrews 1987
Red Crest stock	2729 ± 1.5	Augite porphyritic diorite-gabbro	Corfu and Andrews 1987
Little Vermilion batholith	2731 ± 3	Hornblende tonalite-granodiorite	Corfu and Andrews 1987
Douglas L. pluton	2734 ± 2	Biotite tonalite	Corfu and Stone 1998

**Sanborn-Barrie et al. 2000.

Andrews et al. (1986) defined corridors of regional deformation within the Red Lake greenstone belt through the use of foliation trajectory maps, however, these maps did not distinguish between D_1 and D_2 fabrics or reflect the intensity of the fabrics. As a result, a system of transcurrent deformation zones were proposed and interpreted to host gold mineralization and associated alteration. Sanborn-Barrie et al. (2000) and Dubé et al. (2000) have reassessed these regional deformation zones and have found that there is little evidence for major regional-scale shear zones or mylonite within the belt. Intensity of deformation is typically weak to moderate with variable weak to intense penetrative foliations associated with folding and weak to moderate flattening (Sanborn-Barrie et al. 2000; Dubé et al. 2000).

Regional greenschist-facies metamorphism probably occurred during D_1 (Menard and Pattison 1998). Metamorphic grade increases from greenschist facies in the middle of the greenstone belt to amphibolite facies at the margins of the belt. Metamorphic isograds are concentric to the margins of external granitoid batholiths (i.e., Killala–Baird batholith, Walsh Lake pluton; Hammell Lake batholith) consistent with contact metamorphism during batholith emplacement (Pirie 1982; Andrews et al. 1986; Damer 1997; Menard and Pattison 1998; Menard, Pettigrew and Spray 1999). The contact metamorphic aureole around the Dome stock is only partially preserved due to retrograde carbonate alteration that postdates the intrusion. Three world-class gold deposits—the Campbell and Goldcorp mines and the past-producing Madsen mine—are enclosed within contact metamorphosed amphibolite facies host rocks (Damer 1997; Dubé et al. 2000; Andrews et al. 1986).

A preliminary reconnaissance of the Killala–Baird batholith, Walsh Lake pluton and Dome stock (*see* Figure 22.1) confirms observations by earlier workers (Ferguson 1965; Pirie and Sawitzky 1977; Pirie and Grant 1978b; Riley 1978; Pirie 1982) that the intrusions consist of early, xenolith-rich, gabbroic and dioritic phases intruded by later, marginal phases of quartz porphyritic and/or potassium feldspar porphyritic monzogranite or granodiorite. An exception is the Faulkenham Lake stock (*see* Figure 22.1) which consists of a gneissic core with a marginal granodioritic phase. The marginal phase of the Killala–Baird batholith is an oxidized-type (magnetite-series) quartz porphyritic (± potassium feldspar phenocrysts) biotite-hornblende monzogranite that contains 2 to 5% disseminated magnetite and widespread, patchy to pervasive, disseminated hematite alteration. This marginal phase stands out as a concentric magnetic anomaly on aeromagnetic maps (Ontario Geological Survey 1998) while the interior of the batholith is a broad, moderate, magnetic low. A significant portion of the Walsh Lake pluton (Cat Island pluton), at Ranger Lake, also stands out as a strong, broad magnetic anomaly on aeromagnetic maps (Ontario Geological Survey 1998).

ALTERATION DISTRIBUTION AND MORPHOLOGY

Alteration halos associated with lode gold deposits have been documented in numerous gold camps (Fyon and Crocket 1983; Dubé, Guha and Rocheleau 1987; Colvine et al. 1988; Ames, Franklin and Froese 1991; Fyon et al. 1992; Egerton 1994; Robert 1995; Franklin 1997; Eilu et al. 1999) where lateral alteration zoning can be divided into distal and proximal zones (Eilu et al. 1999). Hydrothermal alteration in the Red Lake greenstone belt is also distributed in regional, zoned alteration envelopes around gold deposits. The distal zone in the Red Lake belt consists of moderate to intense, belt-scale, calcite carbonatization, chloritization and weak potassic alteration. Proximal zones are less extensive and characterized by intense ferroan-dolomite and potassic alteration. Portions of some proximal alteration zones have been affected by contact metamorphism related to external granitoid intrusions. The amphibolitized alteration zones are biotite-rich, carbonatized and contain porphyroblasts of aluminous metamorphic minerals. Multiple periods of silicification and gold mineralization overprint and replace the alteration at the mine- and outcrop-scale.

Results of reconnaissance mapping, described here, has established the gross distribution of the alteration zones. Alteration in mafic and ultramafic metavolcanic rocks is emphasized because these rocks are the major hosts to gold mineralization and are the most abundant lithologies within the alteration zones.

Carbonatization

CALCITE (DISTAL ALTERATION)

Calcite carbonatization is the most widespread alteration in the Red Lake greenstone belt (Figure 22.2) and affects the majority of the Balmer, Ball, Trout Bay, Bruce Channel and Confederation assemblages. Strong to intense calcite alteration is developed in mafic and ultramafic metavolcanic and intrusive rocks. Weak to moderate calcite alteration affects intermediate to felsic metavolcanic rocks, metasedimentary rocks and the margin of the Dome stock and the Howey diorite. Weak, localized calcite alteration is associated with gold mineralization hosted by metasedimentary rocks of the Slate Bay assemblage (Parker 1999a). The past-producing Howey and Hasaga mines (*see* Figure 22.1) are situated within calcite carbonatized wall rocks that host gold-bearing quartz-ankerite and quart-tourmaline veins. The main macroscopic features of distal calcite-altered zones in greenschist-facies mafic and ultramafic metavolcanic rocks are summarized in Table 22.2.

Andrews et al. (1986) reported that mineral assemblages in greenschist-facies, calcite-altered, mafic metavolcanic rocks consist of calcite, chlorite, quartz and subordinate epidote with complete replacement of amphibole and partial replacement of plagioclase. The addition of CO_2 and H_2O and minor depletion of Fe, Mg and Na (Pirie 1982; Andrews and Wallace 1983) characterize the geochemistry of the alteration. Calcite-altered, greenschist-facies, ultramafic rocks contain calcite, chlorite, talc and some sericite or biotite. Calcite alteration persists in amphibolite-facies mafic and ultramafic metavolcanic rocks as patchy disseminated calcite or on pillow selvages, fractures and veinlets. Dubé et al. (2000) reported that disseminated calcite and calcite veinlets are spatially associated with gold-bearing zones in amphibolitized rocks at the Madsen mine.

FERROAN-DOLOMITE (PROXIMAL ALTERATION)

Strong to intense ferroan-dolomite alteration (iron carbonate) (Andrews et al. 1986) affects mafic and ultramafic metavolcanic and intrusive rocks in the Balmer, Ball and Confederation assemblages (*see* Figure 22.2) in the following areas:

1. An area centred on Balmer Lake extending northwest through East Bay to McKenzie Island and enclosing the Campbell, Goldcorp, McMarmac (past-producer) and Cochenour–Willans (past-producer) mines. The gold deposits are located within the proximal zone but near the interface with the distal zone. This area is broadly centred on the closure of a regional, north-northeast-trending F_1 anticline (M. Sanborn-Barrie, GSC, personal communication, 2000) (*see* Figure 22.1) that is transected by a moderate to strong, southeast-striking S_2 fabric and F_2 folds.
2. An area located north of Madsen that encloses several gold prospects. A moderate to strong, east-striking, S_2 penetrative fabric is coincident with intense ferroan-dolomite alteration.
3. An area centred on Middle Bay, at the west end of the greenstone belt, that encloses several, small, past-producing gold mines and prospects. An intense high strain zone (D_2) strikes west-northwest through central Middle Bay for a strike length of approximately 3 km (Parker 1999a).

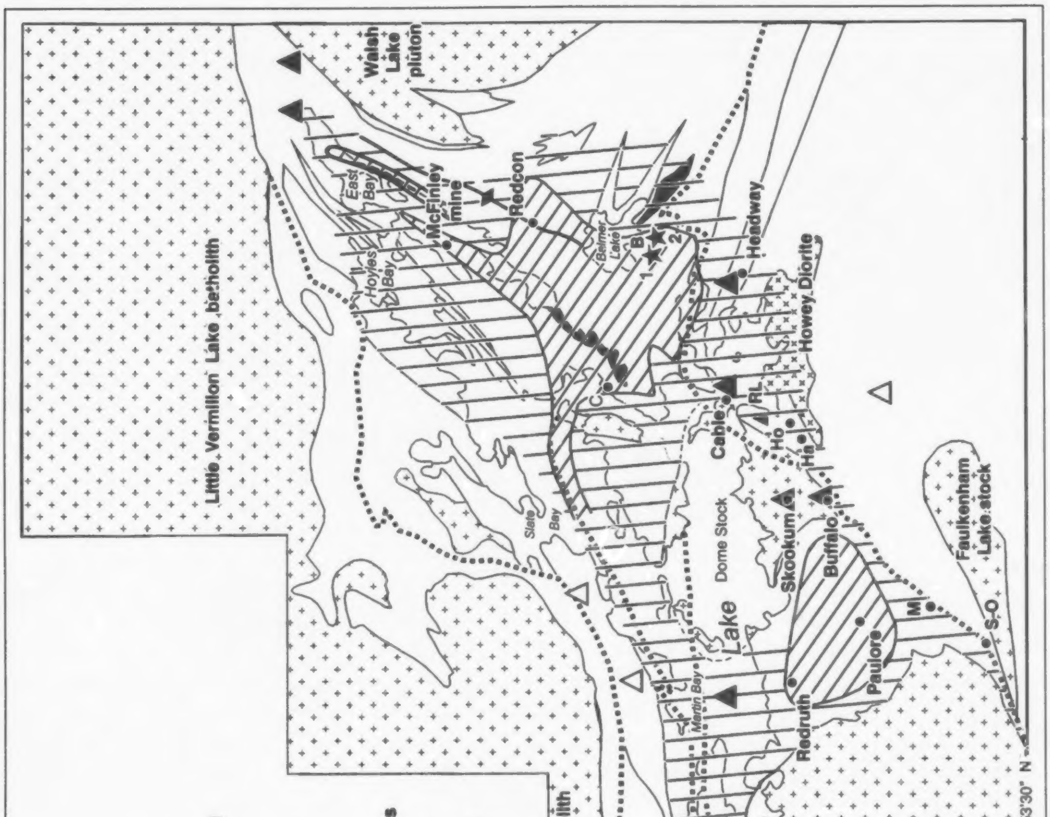

Figure 22.2. Distribution of distal and proximal alteration in the Red Lake greenstone belt (modified after Sanborn-Barrie, Skulski and Parker in press).

Table 22.2. Main macroscopic features of distal and proximal carbonate alteration in greenschist-facies, mafic and ultramafic metavolcanic rocks at Red Lake.

Zone	Features of carbonate alteration	Other features
Distal	Distal zones are dominated by calcite in the following forms: • pervasive replacement of rock matrix; • massive, homogeneous, open-space filling of primary features such as vesicles, pillow selvages, etc.; • replacement of matrix in mafic hyaloclastite and intermediate to mafic pyroclastic rocks; • massive, homogeneous filling of extension veins , complex networks of variably oriented veins and veinlets, and "jigsaw puzzle" breccia veins; • thick coatings on fracture and foliation surfaces. All forms of calcite alteration may occur in a single outcrop with calcite occupying 25 to 60% of the volume of rock. "Jigsaw puzzle" breccia veins are 20 cm to 1.5 m wide and consist of angular to subangular wall rock fragments in a homogeneous, fine- to medium-grained, crystalline, calcite matrix.	Calcite alteration is easily detected by vigorous reaction to dilute hydrochloric acid. Calcite-altered rocks have distinctive, uneven and rubbly weathered surfaces due to recessive weathering of calcite. Pervasively carbonatized rocks are "bleached" to pale grey-green due to the destruction of primary ferromagnesian minerals. Foliation intensity in carbonatized rocks is variable and primary features (i.e., pillows, sedimentary structures, etc.) are commonly preserved. Moderate to intense carbonatization is accompanied by strong to intense brecciation which is most obvious in mafic pillowed flows (Andrews and Wallace 1983).
Proximal	Dominated by ferroan-dolomite in the following forms: • pervasive replacement of rock matrix; • massive, homogeneous, open-space filling of primary features such as vesicles, pillow selvages, etc.; • massive, homogeneous filling of extension veins , complex networks of variably oriented veins and veinlets, and "jigsaw puzzle" breccia veins; • coatings and narrow veinlets on fracture and foliation surfaces. Thick, massive ferroan-dolomite extension veins and jigsaw puzzle breccia veins range from less than 1 m to 18 m in thickness. Stockworks of carbonate veinlets may grade into "jigsaw puzzle" breccia zones. Thick, massive, ferroan-dolomite veins may be enclosed within a complex stockwork of later ferroan-dolomite veinlets that transect the margins of the larger central vein. Carbonate mineral fibres are common in extension veins and have a constant perpendicular orientation to the vein walls. The veins may also display delicate open-space filling textures such as colloform and crustiform banding and cockade breccia textures.	Areas of ferroan-dolomite alteration contain a greater volume of carbonate veins and more abundant disseminated sulphide mineralization than calcite-altered areas. Ferroan-dolomite carbonatized rocks have a distinct orange-brown, rubbly and uneven weathered surface. Pervasively carbonatized rocks are also strongly bleached to pale grey-green, grey-white or buff brown in greenschist-facies rocks. Highly variable, moderate to intense, penetrative foliation is developed in ferroan-dolomite-altered metavolcanic rocks but primary features (i.e., pillows, sedimentary structures, etc.) may be preserved.

Weak to moderate ferroan-dolomite alteration affects 1) intermediate pyroclastic rocks of the Confederation assemblage at the Headway gold prospect; and 2) granodiorite of the Dome stock at the Buffalo gold mine in Heyson Township and the Skookum gold prospect in Dome Township. Pervasive, intense ferroan-dolomite flooding affects the Dome stock at the Cable gold prospect on White Horse Island in Dome Township. Ferroan-dolomite alteration is also reported (Horwood 1941; Lavigne et al. 1986) at gold deposits and past-producing mines in the McKenzie stock. The main macroscopic features of proximal ferroan-dolomite-altered zones in greenschist-facies mafic and ultramafic metavolcanic rocks are summarized in Table 22.2.

The boundary between calcite and ferroan-dolomite zones is abrupt and marked by 1) the disappearance of calcite; and 2) conflicting crosscutting relationships between calcite and ferroan-dolomite veins. Calcite veins may intrude and brecciate ferroan-dolomite veins and vice versa. Ambiguous crosscutting relationships suggest that the 2 types of carbonate alteration were broadly contemporaneous. This interpretation is also supported by the fact that 1) calcite and ferroan-dolomite zones have the same characteristics throughout the greenstone belt; and 2) calcite is ubiquitous as a border phase to ferroan-dolomite at the belt- and outcrop-scale.

Andrews et al. (1986) reported that the mineral assemblages in greenschist-facies, ferroan-dolomite altered, mafic metavolcanic rocks consist of quartz, ferroan-dolomite, sericite/muscovite, biotite and chlorite with the complete replacement of primary amphibole and plagioclase. Wall rocks adjacent to ferroan-dolomite veins may also contain a considerable amount of disseminated calcite. The geochemistry of the alteration consists of variable increases in CO_2, Si, K, and S and depletion of Ca, Mg and Na (Andrews et al. 1986). Intensely carbonatized and deformed ultramafic rocks consist of ferroan-dolomite, dark green chlorite and abundant bright green fuchsite.

Proximal ferroan-dolomite alteration is overprinted by amphibolite-facies contact metamorphism related to the Walsh Lake pluton and Killala–Baird batholith (Andrews et al. 1986). Ferroan-dolomite persists in amphibolite-facies mafic and ultramafic metavolcanic rocks where ferroan-dolomite veins are enclosed within wide alteration halos of biotite-rich and variably calcite-altered wall rock.

Ferroan-dolomite veins in proximal zones are complexly deformed. The following is a description of some of the major features of the deformation.

1. In the Balmertown–Cochenour area, ferroan-dolomite extension veins are discordant to the S_2 foliation ("mine trend") but are typically folded with the S_2 foliation as an axial plane foliation (Andrews and Wallace 1983). The veins contain angular fragments of foliated wall rock that are as strongly foliated as the wall rock outside the veins. These observations suggest that 1) some ferroan-dolomite veins opened perpendicular to the D_2 extension direction during early-D_2 (prior to D_2?) and were subsequently folded by shortening; and 2) that brittle deformation alternated with shortening and foliation development. Some ferroan-dolomite veins may have also filled pre-folded structures.
2. Ferroan-dolomite fault-fill veins transect early carbonate veins and displace or truncate early veins. Many fault-fill veins are planar and subparallel to the S_2 foliation and may be variably boudinaged. These veins consist of carbonate bands separated by foliated wall rock slivers that are parallel to the vein walls. The foliation-parallel veins probably developed subparallel to the extension direction during flattening and opened parallel to foliation planes and faults. Therefore, these veins are interpreted to have formed syn-D_2.
3. Narrow (<6 cm), ferroan-dolomite extension veins transect earlier carbonate veins. These veins may be late-D_2 and formed perpendicular to the extension direction.
4. At Cochenour, ferroan-dolomite veins are displaced or truncated by at least 2 generations of brittle-ductile, tourmaline-filled, hairline faults: 1) an early generation of faults crenulated by the S_2 foliation; and 2) a later generation of planar faults that truncate the folded faults.
5. Multiple stages of carbonate alteration have been recognized at the Campbell and Goldcorp mines (R. Dutka, Campbell mine, personal communication, 2000; B. Dubé, GSC, personal communication, 2000). Horwood (1941) recognized multiple stages of carbonate veining and gold mineralization at the McMarmac mine near Cochenour where some carbonate veins postdate gold mineralization and quartz veining.
6. Thick, foliation parallel ferroan-dolomite veins are subparallel to the dominant S_2 foliation but also occur along a strong north- to northeast-striking S_1 fabric in the East Bay and Cochenour areas. This indicate that some carbonatization occurred during D_1 or that carbonate was emplaced in pre-existing D_1 structures.

The above observations indicate that D_2 was a complex event characterized by episodic periods of brittle deformation. The presence of multiple ages of carbonate veins indicates continuous carbonatization during deformation.

Potassic Alteration

Potassic alteration affects metavolcanic rocks in the Balmer, Ball, Trout Bay, Bruce Channel and Confederation assemblages and occurs in distal and proximal alteration zones. Distal calcite alteration in greenschist-facies mafic metavolcanic rocks is commonly accompanied by weak potassic metasomatism consisting of incipient sericitization of chlorite and plagioclase. Proximal, ferroan-dolomite zones in greenschist-facies mafic metavolcanic rocks are accompanied by strong to intense potassic alteration consisting of disseminated sericite/muscovite and some biotite accompanied by the destruction of amphibole and plagioclase (Andrews et al. 1986). Pervasive potassic alteration in ferroan-dolomite-altered ultramafic rocks consists of bright green fuchsite instead of sericite. Some strongly carbonatized and sericitized ultramafic rocks are bleached pale grey with numerous thick, anastamosing, fuchsite bands. These rocks are very hard and appear silicified but are soft and talcose on fresh surfaces.

Intermediate to felsic metavolcanic and metasedimentary rocks are also affected by potassic alteration. Felsic metavolcanic rocks in the Ball assemblage are strongly sericitized and have a buff grey or yellow-green, translucent, waxy appearance (Parker 1999a). Intense fuchsite-bearing zones are common in intermediate to felsic, volcaniclastic, metasedimentary rocks that contain detrital chromite in Ball and Bruce Channel assemblages. Felsic rocks in the Balmer assemblage are sericitized and may contain strong biotite alteration in small patches or along fractures and foliation surfaces.

Proximal ferroan-dolomite zones in amphibolite-facies, mafic and ultramafic metavolcanic rocks are accompanied by moderate to intense potassic metasomatism consisting of pervasive biotite ± muscovite. Altered rocks contain 5 to 50% modal biotite at the expense of amphibole and plagioclase (Andrews et al. 1986). Biotitic rocks are typically hard and fine-grained with a distinctive brown-grey weathered surface and purple-brown fresh surface. Biotite-altered rocks may also contain patchy, sericitic, bleached areas on weathered surfaces. The biotite alteration is typically pervasive but may occur along fractures and zones of primary permeability such as pillow selvages. Strong to intense biotite ± calcite ± ferroan-dolomite alteration halos enclose ferroan-dolomite veins in amphibolite-facies rocks. These alteration halos may extend several tens of metres outward from the carbonate veins depending on the thickness and volume of the veins. This effect is best observed at the McFinley and Redcon gold properties at East Bay on Red Lake (*see* Figure 22.1).

Aluminous Biotite Alteration

Biotitic altered zones in amphibolite-facies metavolcanic rocks may also contain variable amounts of aluminosilicate minerals such as andalusite, staurolite and cordierite and other minerals such as garnet, chloritoid, cummingtonite and anthophyllite. This aluminous biotite alteration has been identified in the Madsen, East Bay and Balmertown areas in the Balmer assemblage (Andrews et al. 1986; Dubé et al. 2000) and at the Rowan and Mt. Jamie mines in the Ball assemblage (Wallace 1982; Parker 1999a) (Figure 22.1). These rocks also contain equant porphyroblasts of extremely calcic plagioclase (An_{50} to An_{93}) at the Campbell and Goldcorp mines whereas least altered rocks contain sodic plagioclase (Damer 1997). Diversity of porphyroblasts is due to the metamorphic response of several altered protoliths. Hydrothermal fluids have altered metavolcanic and intrusive protoliths along fractures and zones of primary permeability such as pillow selvages and inter-pillow spaces. The margins of pillows are typically bleached to pale grey due to the destruction of amphibole. Andalusite porphyroblasts are commonly concentrated within these bleached zones. The interiors of pillows are less altered and contain abundant disseminated biotite and garnet porphyroblasts. Staurolite porphyroblasts occur in bleached and biotitic areas.

The geochemistry of altered mafic and ultramafic metavolcanic rocks hosting aluminosilicate minerals is characterized by 1) Na_2O, MgO and CaO depletion (Penczak 1996; Durocher 1983; Andrews et al. 1986) caused by the destruction of feldspar and amphibole by alteration reactions; 2) K_2O enrichment due to potassic metasomatism (Penczak 1996; Durocher 1983; Andrews et al. 1986); and 3) residual enrichment of relatively immobile Al_2O_3 due to significant losses of Na_2O, MgO and CaO. Subsequent metamorphism of these aluminous, potassic, altered rocks resulted in the growth of porphyroblastic aluminosilicate minerals and biotite. Biotitic rocks, with or without aluminous metamorphic mineral assemblages, contain variable amounts of disseminated sulphide minerals and trace to low anomalous gold values (Dubé et al. 2000; Parker, unpublished data, 1999). In general, these altered rocks only contain gold where they are overprinted by late silicification.

Aluminous potassic alteration is also present in the Bruce Channel assemblage at Cochenour. Intensely altered intermediate to felsic metavolcanic rocks known locally as "point rock" are pale grey, siliceous, and devoid of any primary structures. "Point rock" is strongly sericitized and may contain abundant andalusite porphyroblasts and variable amounts of disseminated fuchsite. An analysis of "point rock" (Lavigne et al. 1986) indicates that it contains 73.8 wt.% SiO_2 , 14.5 wt.% Al_2O_3 and 4.15 wt.% K_2O with Na_2O and CaO contents below 0.20 wt.%.

Silicification

There are 2 types of silicification within proximal alteration zones: barren, pervasive silicification and pervasive silicification and quartz veining associated with sulphide mineralization and gold.

Barren pervasive silicification occurs within proximal ferroan-dolomite zones where it is confined to relatively small (<4 m wide), irregular and discontinuous areas with diffuse, gradational boundaries. Andrews et al. (1986) reported that silicified zones were hundreds of metres in size with mafic metavolcanic rocks containing 55 to 60 wt.% SiO_2. An anomalous proportion of quartz veins and veinlets is typically associated with these zones. Silicified mafic metavolcanic rocks contain buff-brown siliceous patches or may be pervasively bleached to grey-white or yellow-green whereas silicified ultramafic rocks are purple-brown or green. Most silicified rocks are extremely hard with splintery, conchoidal fractures on fresh surfaces. Silicified rocks are typically strongly deformed and primary structures such as pillow selvages may be obliterated, however, quartz-filled amygdules and varioles are commonly preserved. Two samples taken by the author from silicified, pillowed basalt near the Redruth gold prospect contain 71.21 and 78.38 wt.% SiO_2. These silicified rocks show no significant addition of CO_2 but strong depletion of CaO, Na_2O, MgO, MnO and Fe_2O_3.

Pervasive wall rock silicification and some quartz veining may be due to the release and remobilization of silica from mafic and ultramafic rocks by alteration reactions during carbonatization (Robert 1995; Eilu et al. 1999). Robert (1995) states that this form of silicification results in, "a local increase in the abundance of quartz, either as quartz-flooding of the rock matrix or as abundant quartz veinlets." Apparent silicification may also result from residual enrichment of SiO_2 due to the removal of large quantities of Ca, Mg, Fe and Na during alteration (Franklin 1997; Andrews et al. 1986).

Silicification associated with gold and sulphide mineralization (i.e., arsenopyrite, pyrite, pyrrhotite) is a later alteration that postdates most of the ferroan-dolomite and potassic alteration. Alteration zones are typically barren of gold unless they have been silicified. The silicification occurs as extension and fault-fill quartz veins; "jigsaw puzzle" breccia veins; open-space filling of primary features such as vesicles and inter-pillow spaces; or as pervasive replacement of ferroan-dolomite. Silicified gold-bearing zones are overprinted by S_2 fabrics; displaced along the S_2 foliation; or transected by S_2 shearing (R. Dutka, Campbell mine, personal communication, 2000).

Silicification occurred throughout the history of the greenstone belt with quartz veins affecting late, unaltered, mafic dikes that transect S_2 structures and alteration. Gold occurrences are situated in all supracrustal assemblages and intrusions emplaced at about 2720 Ma (i.e., Dome stock). Horwood (1941) recognized multiple stages of quartz veining and gold mineralization in the greenstone belt and documented 3 separate periods of silicification and gold mineralization at the McMarmac mine near Cochenour. Horwood (1941), Andrews et al. (1986) and Lavigne et al. (1986) provide descriptions of silicified gold-bearing zones at the various mines in the belt.

Tourmaline

Abundant black tourmaline is a relatively late alteration superimposed on proximal, ferroan-dolomite alteration zones in amphibolite-facies rocks. Tourmaline also overprints granitoid intrusions such as the Dome and McKenzie stocks; the Howey diorite; and the Abino and Wilmar dikes.

Tourmaline occurs in the following forms:

- in narrow fractures, faults and shear bands and auriferous crack-seal tourmaline-quartz veins, i.e., the Dome stock, McKenzie Island stock, Howey diorite, Wilmar dike;
- in thick zones of massive tourmaline-flooding, i.e., the Cable gold prospect in the Dome stock where angular fragments of carbonatized granodiorite are embedded in massive, fine-grained tourmaline;
- in brittle-ductile fractures and hairline faults that are planar or folded and truncate and thicken ore zones, i.e., at the Campbell and Goldcorp mines;
- as single, disseminated, euhedral porphyroblasts up to 1 cm in size or as thick clusters of crystals that overprint foliations in mafic and ultramafic metavolcanic rocks, i.e., at Madsen and in outcrops on the Nungesser road;
- as pervasive replacement of pillow selvages in mafic and ultramafic metavolcanic rocks, i.e., at Madsen and the Redcon property;
- as massive tourmaline veins that transect ferroan-dolomite veins, i.e., at the Redcon property;
- as randomly oriented euhedral crystals on foliation and fracture surfaces, i.e., at Madsen;
- as radiating sprays of acicular crystals in diopside veins, i.e., at Madsen.
- as acicular crystals in sulphide zones hosted by metavolcanic rocks in the Confederation assemblage i.e., Killoran creek occurrence (Parker 1999b).

Tourmaline commonly occurs in gold-bearing quartz veins but is also associated with barren veins.

Skarn

SKARN IN CHEMICAL METASEDIMENTARY ROCKS

This type of skarn consists of pyroxene-rich, calc-silicate mineral assemblages in dolomitic marble interlayered with chert and chert-magnetite iron formation in the Ball, Slate Bay and Balmer assemblages. Riley (1975) noted this type along the south margin of the Hammell Lake batholith where marble units are replaced by coarse diopside and wollastonite. Diopside skarn interlayered with pyrrhotite-rich chert, on the northeast side of Pipestone Bay, is reported by Riley (1970) to be 200 feet thick. Riley (1978) also mapped skarn in dolomitic marble, along the west margin of the Dome stock, in Fairlie Township. Sanborn-Barrie, Skulski and Parker (in press) identified diopside skarn in possible stromatolitic marble north of Slate Bay along the margin of the Little Vermilion batholith. Skarnified chert-magnetite iron formation interlayered with clastic metasedimentary rocks host gold and silver mineralization at the Slate Bay occurrence on Slate Bay of Red Lake (Atkinson, Parker and Storey 1990).

SKARN IN CARBONATIZED MAFIC AND ULTRAMAFIC METAVOLCANIC ROCKS

This skarn is best developed within the metamorphic aureole of the Killala–Baird batholith from Johnson Lake and Trout Bay to Madsen (Figure 22.3). The contact metamorphic aureole is irregular and extends outward from the batholith for about 1.5 km (Andrews et al. 1986) but the skarn is typically proximal to the batholith contact. At Madsen, the skarn and metamorphic aureole extends outward from the batholith for about 1.5 km along the Balmer–Confederation assemblage unconformity (*see* Figure 22.3) which may have served as a permeable conduit for metasomatic hydrothermal fluids.

The skarn consists of high temperature, anhydrous assemblages of coarse diopside (0.3–4 cm), orange-brown garnet (andraditic grossular?) ± calcite and quartz that replaces carbonatized mafic and ultramafic metavolcanic rocks and overprints aluminous biotite alteration. The carbonate matrix of "jig-saw puzzle" breccia veins is commonly replaced by diopside, garnet and quartz. Massive diopside veins (1 cm to 1.5 m thick) composed of coarse diopside ± calcite, quartz and tourmaline and stockworks of intersecting diopside-filled fractures transect and replace ferroan-dolomite veins at Madsen. The anhydrous assemblage is overprinted and retrograded by a low temperature hydrous assemblage of epidote, tremolite, actinolite/hornblende, magnetite and sulphide minerals characteristic of skarns (Einaudi, Meinert and Newberry 1981; Mueller 1991; Meinert 1992). Narrow (< 2 cm) diopside veins in mafic and ultramafic rocks may contain dark green amphibole rims or halos. The skarn assemblages formed as a result of calcium metasomatism accompanied by some silicification.

The skarns are variably deformed. Strain intensity increases toward the Killala–Baird batholith where a strong penetrative foliation is associated with batholith-induced flattening. The most strongly foliated rocks occur within 150 m of the batholith contact where diopside veins are 1) boudinaged, foliation-parallel veins; and/or 2) folded with the foliation as the axial plane foliation. Some diopside veins at Madsen are relatively undeformed and transect the foliation. These observations indicate that diopside veins may be syntectonic with respect to the Killala–Baird batholith. Deformed skarn assemblages are transected by pink, granitic Killala–Baird dikes that are undeformed or buckled and displaced along the foliation at the margin of the batholith.

The Madsen gold mine is hosted within skarnified mafic and ultramafic metavolcanic rocks that were affected by carbonatization and potassic alteration prior to skarnification. Dubé et al. (2000) reported that alteration at the Madsen gold mine could be divided into an outer, distal, aluminous alteration zone and an inner proximal alteration zone. The outer zone is characterized by aluminous biotite alteration described above (*see* "Aluminous Biotite Alteration"). The inner zone is characterized by metasomatic layering that encloses discrete ore zones and consists of alternating amphibole- and biotite-rich layers that may form stockworks or breccia textures. These zones contain actinolite, hornblende, microcline, calcite and tourmaline and disseminated diopside crystals up to 7 to 8 cm long or diopside veins (Dubé et al. 2000). Calcite alteration is spatially related to gold mineralization and increases in intensity toward gold-bearing zones. Dubé et al. (2000) concluded that the alteration at Madsen is analogous to high temperature (400 to 650°C) gold deposits and gold-skarn deposits hosted by mafic metavolcanic rocks similar to those described by Mueller and Groves (1991) and Mueller (1997). The skarn assemblage and associated gold mineralization at Madsen is deformed (Dubé et al. 2000) but may have formed during an early stage of deformation.

Numerous pits and trenches have been sunk on disseminated sulphide mineralization in altered mafic metavolcanic flows hosting calcite veins and calc-silicate skarn south of Wolf Bay on Red Lake (Parker 1999b). The mafic flows appear to be pervasively biotite-altered and have a purple-brown fresh surface transected by a network of pale green epidote- and diopside-filled fractures and patches of epidote, diopside and garnet. The skarnified mafic rocks are typically very hard and host variable amounts of disseminated sphalerite, galena, pyrite, pyrrhotite and arsenopyrite with erratic gold and silver values.

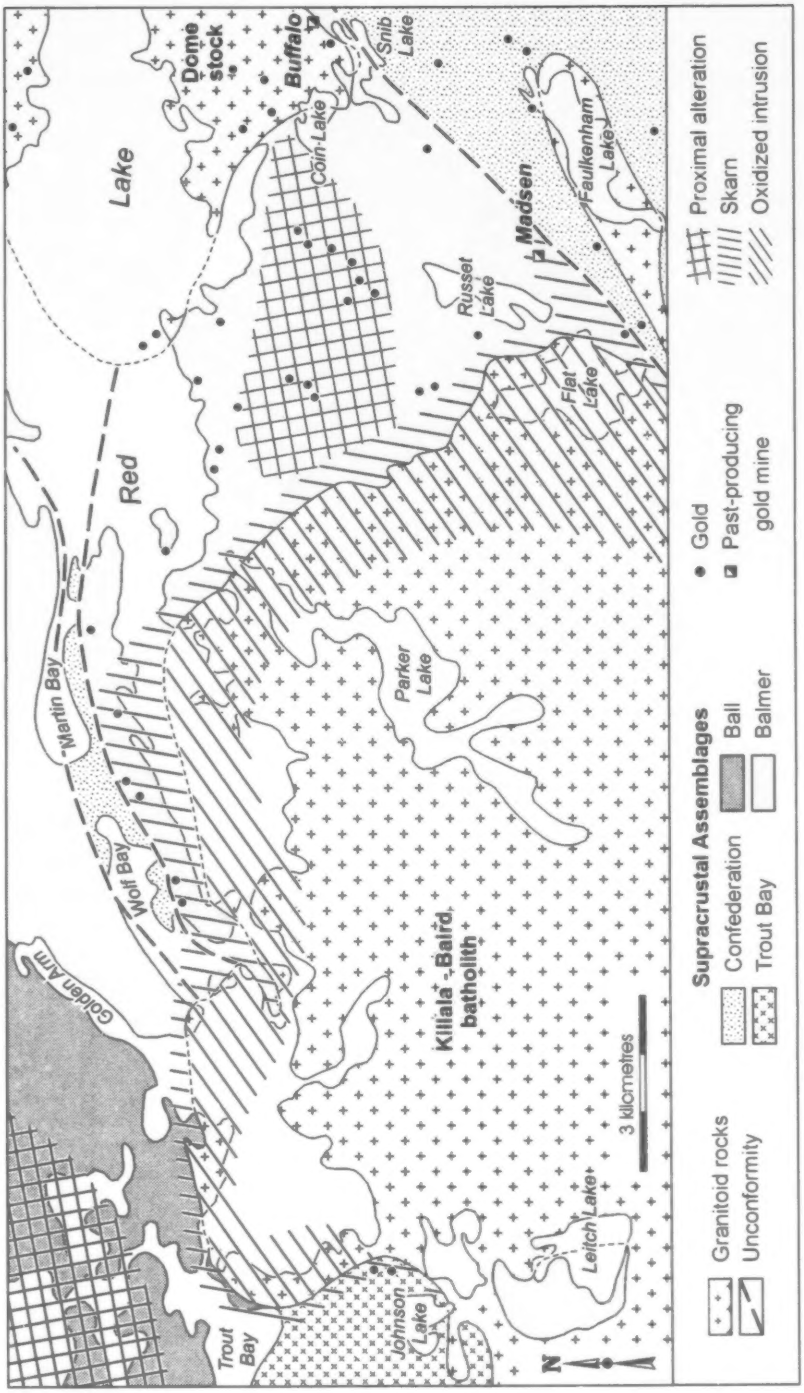

Figure 22.3. General geology in the vicinity of the Killala–Baird batholith including distribution of skarn, alteration and gold deposits.

Sulphide minerals also occur in veinlets and on fracture and foliation surfaces. The sulphide mineralization and associated, fracture-controlled, epidote alteration and skarn are extensive but appear to be relatively late.

Skarn in carbonatized mafic metavolcanic rocks has been recognized in the metamorphic aureole of the Walsh Lake pluton. Menard and Pattison (1998) identified a prograde skarn assemblage of grossular, diopside, calcite and epidote overprinted by retrograde tremolite about 2 km north of Keg Lake. The author observed large 1 to 2 m patches of epidote-diopside-garnet skarn overprinted by porphyroblastic tourmaline on the Nungesser road. A 1 to 2 m wide breccia consisting of angular fragments of garnetiferous mafic metavolcanic rocks embedded in a fine-grained, pale green diopside (tentative identification) matrix was also observed at the Redcon gold property (*see* Figure 22.1).

Amphibole Veins

Large areas of spectacular amphibole veining are present in amphibolite-facies, altered mafic and ultramafic metavolcanic rocks at East Bay on Red Lake and at Madsen. The veins dominantly affect Balmer assemblage rocks but occur in intermediate to felsic metavolcanic rocks of the Confederation assemblage at Madsen. The amphibole veining consists of narrow fractures (<1 cm to 6 cm) that form complex, interconnected, web-like meshes. The veins dominantly contain dark green actinolite, hornblende ± magnetite, quartz, calcite, epidote, diopside and sulphide minerals. The veins are rimmed by positive weathering alteration halos of dark green amphibole that extend outward from the fracture for 1 to 4 cm. Dark green amphibole assemblages also fill primary open spaces such as pillow selvages, inter-pillow spaces and vesicles. In some cases the amphibole veins contain garnet and rare staurolite porphyroblasts. Amphibole veining is ubiquitous over a very large area east of East Bay in the vicinity of the Redcon property. Amphibole veining at Madsen is confined to stockwork zones that are a few metres wide. The veins are typically randomly oriented with randomly oriented amphibole crystals that transect foliation, however, amphibole veins are also aligned along penetrative planar fabrics. Deformed veins impart a banded or layered appearance to the host rocks.

The amphibole veins overprint biotite-rich altered rocks and aluminous biotite alteration. The veins also transect and replace diopside veins at Madsen and ferroan-dolomite veins at Madsen and the Redcon property. Ferroan-dolomite veins are also transected by numerous, narrow quartz veins with thick tremolite/actinolite rims that may contain fine-grained diopside. Small specks of visible gold may be present in actinolite rims at the Redcon property.

The majority of amphibole veins may have formed during a retrograde, hydrous, metasomatic event that occurred after peak, prograde metamorphism. Veins that contain garnet and staurolite may have formed slightly before peak metamorphism. The origin of this intense fracturing is speculative but may be due to 1) hydraulic fracturing caused by over-pressured hydrothermal fluid (Phillips 1972); or 2) by "thermal-cracking" where hot rocks are cooled by circulating fluids in fractures that formed during thermal contraction (Barrie et al. 1997).

Other Alteration Types

Synvolcanic iron enrichment is associated with exhalative, chert-magnetite horizons in the Bruce Channel and Balmer assemblages. At Cochenour, intermediate pyroclastic rocks of the Bruce Channel assemblage are situated stratigraphically below chert-magnetite iron formation and host spectacular discordant veins and irregular patches of dark green chlorite-magnetite ± garnet. The chlorite-magnetite alteration completely replaces tuffaceous layers or preferentially replaces matrix or individual clasts. Iron enrichment alteration in the Balmer assemblage is metamorphosed to an assemblage of amphibole-garnet ± magnetite and occurs as irregular patches in felsic pyroclastic rocks. These rocks are also situated stratigraphically below chert-magnetite iron formation at Hoyles Bay on Red Lake (Pirie and Sawitzky 1977). Metamorphosed iron enrichment alteration was also recognized in intermediate to felsic Bruce Channel rocks located northeast of Balmer Lake.

Localized, synvolcanic alteration associated with exhalative, barren, iron sulphide mineralization and disseminated zinc and copper sulphide mineralization has been identified in the Confederation assemblage along the southeast flank of the Red Lake greenstone belt (Parker 1999b).

SUMMARY AND DISCUSSION

Several workers (Kerrich et al. 1981; Pirie 1982; MacGeehan and Hodgson 1981; Penczak and Mason 1997, 1999) have suggested that the Red Lake greenstone belt was affected by early gold mineralizing events. They suggest that much of the gold was deposited during volcanism and/or before the earliest recognized deformation and metamorphism. Penczak and Mason (1997, 1999) have suggested that the Campbell mine is an epithermal gold deposit analogous to Cenozoic low-sulphidation gold deposits. Andrews et al. (1986) suggested that gold deposition postdated volcanism and was associated with batholith emplacement. Menard, Pettigrew and Spray (1999) have suggested that the major gold mineralizing event occurred during D_2 (2720 to 2715 Ma) with another mineralizing event at approximately 2700 Ma. This author joins the debate with some tentative interpretations regarding the timing of alteration and gold mineralization.

Timing of Alteration

Calcite and ferroan-dolomite alteration are broadly contemporaneous. The belt-wide carbonate alteration event occurred during D_2 after the intrusion of the Dome stock (2718 ± 1 Ma) and McKenzie stock (2720 ± 2 Ma) (Corfu and Wallace 1986) since carbonate affects both intrusions. Carbonate alteration also affects the majority of supracrustal assemblages in the greenstone belt and is not confined to specific assemblages. Some carbonate alteration may have been emplaced in pre-existing D_1 structures at East Bay but carbonate also affects rocks as young as the Wilmar dike at 2701 ± 1.5 Ma (Corfu and Andrews 1987). Carbonatized metavolcanic rocks are replaced by calc-silicate skarn that was formed during the intrusion of the Kilalla–Baird batholith (2704 ± 1.5 Ma) (Corfu and Andrews 1987) and the Walsh Lake pluton at 2699 Ma (Noble 1989). Therefore, the timing of significant carbonate alteration can be bracketed between 2718 and 2704 Ma. Barren, pervasive silicification, some quartz veining and potassic metasomatism were coeval with the carbonate alteration event.

Ferroan-dolomite extension veins are folded by the "mine trend" (S_2) fabric in the Balmertown–Cochenour area suggesting that these veins are early syntectonic. Some syntectonic, planar, fault-fill and extension carbonate veins transect early folded veins. Silicification associated with gold and sulphide mineralization typically postdates ferroan-dolomite and potassic alteration. Tourmaline affects the Dome and McKenzie stocks and the Wilmar dike (2701 ± 1.5 Ma) (Corfu and Andrews 1987) and occurs in gold-bearing quartz veins that transect these intrusions. This indicates that tourmaline was deposited after 2701 ± 1.5 Ma. Tourmaline is typically posttectonic and overprints all deformation fabrics. Some tourmaline is also syntectonic because it is hosted by faults that are folded by the S_2 foliation. The relationship between alteration and deformation fabrics indicate that hydrothermal alteration and gold mineralizing events occurred during a prolonged and complex period of deformation.

Aluminous biotite alteration zones hosting metamorphic aluminosilicate minerals are interpreted by Andrews et al. (1986), Penczak (1996) and Damer (1997) to represent metamorphosed proximal alteration zones formed during ferroan-dolomite carbonatization and associated potassic alteration. These alteration zones are within the contact metamorphic aureoles of the Killala–Baird batholith and the Walsh Lake pluton. MacGeehan, Sanders and Hodgson (1982) suggested that the aluminosilicate-bearing rocks represented synvolcanic alteration associated with "chemical sedimentary gold ore zones". This interpretation is debatable since mineralized zones previously identified as "chemical sedimentary gold ore zones" have been demonstrated to be strongly altered and deformed mafic metavolcanic rocks (Lavigne and Crocket 1983).

There have been attempts (Corfu and Andrews 1987) to constrain the timing of gold mineralization and alteration by conducting U-Pb age estimates on zircon, baddeleyite, rutile, titanite and monazite in dikes that transect deformed, altered and mineralized metavolcanic rocks (Table 22.3). This U-Pb dating has yielded mixed and somewhat ambiguous results due to the fact that some dikes only contain titanite or contain multiple zircon populations; inherited zircons; and zircons that have been isotopically disturbed by metamorphism and/or alteration events (Corfu and Andrews 1987; *see* Table 22.3). Several U-Pb age estimates obtained from dikes in the Red Lake gold camp do not represent definitive ages and are open to multiple interpretations.

For example, the Wilmar (Cochenour–Willans mine; 1300-foot level) and Abino (Abino prospect) granodiorite dikes contain gold-bearing quartz veins and transect altered and deformed metavolcanic rocks. Corfu and Andrews (1987) reported that 2 populations of zircons were extracted from these dikes (*see* Table 22.3). The first zircon population gave ages, similar to the Confederation assemblage, between 2746 and 2731 Ma for the Wilmar dike and 2739 and 2728 Ma for the Abino dike. The second zircon population yielded ages of 2701 ± 1.5 Ma and 2718 +12/-6 Ma for the Wilmar and Abino dikes, respectively. Alteration of the Abino dike produced a secondary mineral assemblage of sericite, biotite, chlorite and calcite accompanied by rutile, titanite and monazite that formed at about 2718 +7/-4 Ma. Therefore, the emplacement age of the Abino dike was interpreted to be 2720 +7/-5 Ma (Corfu and Andrews 1987). The Wilmar dike is also altered but contains rutile with low U-content and does not contain titanite or monazite, therefore, an age for the alteration event could not be obtained. Corfu and Andrews (1987) interpreted these data in 2 ways: 1) the dikes were magmatically emplaced at 2720 +7/-5 Ma (Abino) and 2701 ± 1.5 Ma (Wilmar), inherited Confederation-age xenocrystic zircons and were altered after emplacement; or 2) the dikes are Confederation age but experienced alteration events between 2720 and 2700 Ma that caused partial resetting of the old zircons and crystallization of new zircons. Another example of ambiguity is the U-Pb age for the diorite dike that transects deformation and mineralization at the Madsen mine. This dike contains inherited zircons, therefore, its emplacement age was estimated from titanite at 2699 ± 4 Ma (Corfu and Andrews 1987; *see* Table 22.3). However, the titanite may have been produced during metamorphism or alteration and may not represent an emplacement age. These examples illustrate that U-Pb age dates from these dikes are interpretations and are neither clear or unambiguous.

Timing of Metamorphism and Deformation

BALMERTOWN–COCHENOUR–EAST BAY

The relative timing of metamorphism and deformation is constrained by regional syn- and posttectonic textures in aluminous biotite alteration zones. Garnet porphyroblasts grew along the southeast-striking "mine trend" (S_2) but also overprint this foliation. Damer (1997) documented the same relationships for the majority of metamorphic minerals (i.e., andalusite, chloritoid, staurolite, cummingtonite) at the

Table 22.3. Descriptions and radiometric ages for minor intrusive rocks in the Red Lake greenstone belt.

Intrusive Rocks	Radiometric Age (Ma)	Rock Types and Descriptions	References
Diorite dike, Madsen (immediately east of headframe)	1. Titanite = 2699 ± 4 2. Inherited zircons = 2837 and 2856	Crosscuts deformed metavolcanic rocks and ore bodies. Dike is reported to be undeformed.	Corfu and Andrews 1987
Wilmar granodiorite dike, Cochenour–Willans mine (1300-foot level)	1. Type 1 zircons = 2731 to 2746 2. Type 2 zircons = 2701± 1.5	Altered to albite, sericite, carbonate; hosts gold-bearing quartz-tourmaline veins; crosscuts deformed metavolcanic rocks.	Corfu and Andrews 1987
Plagioclase-phyric mafic dike, Rowan mine (immediately east of headframe)	Titanite = 2705 ± 8	Large, acicular, unaltered plagioclase phenocrysts. Crosscuts deformed and mineralized metavolcanic rocks.	Corfu and Andrews 1987
Quartz-feldspar porphyry dike, Goldcorp mine (16-level)	Zircon = 2714 ± 4 Ma (possible inherited zircons or isotopic disturbance of zircons)	Moderate to intense muscovite-biotite alteration; contains a weak foliation; crosscuts deformed and mineralized metavolcanic rocks.	Corfu and Andrews 1987
Abino granodiorite dike, Abino prospect decline	1. Type 1 zircons =2728 and 2739 2. Type 2 zircons = 2718 +12/-6 3. Titanite, monazite, rutile = 2718 +7/-4 4. Common age for Type 2 zircons, titanite, monazite and rutile =2720 +7/-5	Pervasively altered (sericite, biotite with subordinate chlorite and calcite); hosts gold-bearing quartz veins and disseminated sulphide minerals. Crosscuts altered and deformed metavolcanic rocks.	Corfu and Andrews 1987
Red Crest stock	1. Zircon = 2729 ± 1.5 2. Titanite = 2725 ± 3	Altered gabbroic to dioritic intrusion that hosts gold-bearing quartz veins.	Corfu and Andrews 1987
Brewis quartz-feldspar porphyry, Balmer Lake	Zircon = 2742 +3/-2	Strongly sericitized and chloritic; hosts quartz veins.	Corfu and Andrews 1987
Felsic dike, Rahill Bay	Zircon = 2757 +9/-4 (heterogeneous zircons)	Isoclinally folded.	Corfu and Wallace 1986
Quartz gabbro ("Campbell–Dickenson diorite")	1. Zircon = 2872 2. Baddeleyite = 2860 3. Age estimate = 2870 ± 15 (possible isotopic disturbance of zircon and baddeleyite).	Intensely altered and deformed; contains andalusite and chloritoid. May be an intensely altered supracrustal rock.	Corfu and Andrews 1987

Goldcorp mine. Menard and Pattison (1998) noted that the cores of some garnets overprint an early S_1 foliation while garnet rims overprint the S_2 foliation. These relationships indicate that syntectonic metamorphic minerals crystallized during the development of penetrative fabrics, and that metamorphic mineral growth outlasted deformation. Damer (1997) and Menard and Pattison (1998) identified distinct inclusions of gold and sulphide minerals in the cores of garnet porphyroblasts which suggests that garnet growth occurred during the mineralizing event. Damer (1997) suggested that the metamorphic minerals were formed during contact metamorphism imposed by the Walsh Lake pluton.

MADSEN

At Madsen, andalusite porphyroblasts in aluminous biotite alteration zones have crystallized along an early S_1 foliation that is crenulated by a S_2 foliation. The S_2 foliation is interpreted to have formed at approximately 2718 Ma (M. Sanborn-Barrie, GSC, personal communication, 2000). Porphyroblastic garnet and staurolite crystallized along the S_2 foliation and overprints it. If deformation occurred at 2718 Ma, then metamorphic mineral growth along S_2 may have also occurred at ca. 2718 Ma. This interpretation would rule out the Killala–Baird batholith (2704 Ma) as a heat source for metamorphism. However, skarn and amphibole veins spatially associated with the Killala–Baird batholith overprint metamorphic minerals and are variably deformed. Alternative interpretations are: 1) that a period of syntectonic metamorphism is attributable to the undated Faulkenham Lake stock, southeast of Madsen; or 2) that D_1, D_2 and metamorphism are broadly coeval at 2704 Ma, and related to a single contact metamorphic and metasomatic event related to the Killala–Baird batholith. Foliation parallel andalusite, garnet and staurolite may indicate that peak metamorphism occurred during D_1 and early-D_2 while posttectonic garnets indicate that peak metamorphism outlasted D_1 and D_2. More work must be completed at Madsen to clarify relationships between metamorphism and deformation.

Timing of Skarn

Skarn in metamorphosed dolomitic marble has been documented along the margins of the majority of intrusions in the Red Lake greenstone belt, regardless of their age (*see* "Skarn"). Metasomatism and skarnification of previously carbonatized metavolcanic rocks occurred during the intrusion of the Killala–Baird batholith and the Walsh Lake pluton. Calc-silicate skarn assemblages overprint and replace calcite carbonatized mafic and ultramafic metavolcanic rocks and ferroan-dolomite veins adjacent to the Killala–Baird batholith at Madsen. Later amphibole veins are typically confined to amphibolitized rocks and overprint ferroan-dolomite veins, prograde calc-silicate assemblages, prograde metamorphic minerals and potassic alteration. These veins appear to be relatively late and may be associated with a retrograde metamorphic event that followed prograde contact metamorphism. The skarn assemblage is variably deformed and may have formed during deformation.

The marginal, porphyritic, granitic phase of the Killala–Baird batholith is weakly to moderately altered. Granitic rocks are variably hematized; feldspars are weakly to moderately sericitized; and amphibole and biotite are replaced by epidote and chlorite. Thick zones of epidote alteration occur in irregular patches and veins or epidote is disseminated in large areas of the intrusion. This alteration may represent a weak endoskarn that was formed during the introduction of calcium from the host rocks (Einaudi, Meinert and Newberry 1981).

Timing of Gold Mineralization at Madsen

The Madsen gold deposit is hosted by amphibolitized, mafic to ultramafic, metavolcanic wall rocks that contain high temperature calc-silicate (skarn) mineral assemblages about 1.5 km from the margin of the Killala–Baird batholith (*see* Figure 22.3). Skarnification is superimposed on previously altered (carbonate and potassic alteration) metavolcanic rocks. Dubé et al. (2000) reported that proximal alteration at Madsen was characterized by metasomatic layering containing actinolite, hornblende, microcline, calcite and tourmaline and disseminated diopside crystals or diopside veins (Dubé et al. 2000). Dubé et al. (2000) concluded that the alteration at Madsen is analogous to high temperature (400 to 650°C) gold deposits and gold-skarn deposits hosted by mafic metavolcanic rocks (Mueller and Groves 1991).

The oxidized, magnetic character of the marginal phase of the Killala–Baird batholith is a potential, favourable source for gold. Hattori (1987) and Cameron and Hattori (1987) have shown that magnetic, felsic intrusions are spatially, temporally and probably genetically related to gold mineralization in several gold camps within the Superior Province. The oxidized, hydrous and CO_2-rich parent magmas of these intrusions may have favoured the assimilation of gold into the partial melt and its partitioning into magmatic aqueous fluids (Cameron and Hattori 1987). Fluids such as these may have been responsible for the skarnification and gold mineralizing event at Madsen.

The gold mineralizing event at Madsen may have been synchronous with contact metamorphism and metasomatic skarnification associated with the intrusion of the Killala–Baird batholith at 2704 ± 1.5 Ma (Corfu and Andrews 1987). Sanborn-Barrie et al. (2000) and Dubé et al. (2000) have reported that gold at Madsen is deformed by a D_2 fabric interpreted to have formed at 2718 Ma (M. Sanborn-Barrie, GSC, personal communication, 2000), however, this same fabric also deforms skarn. More work must be done to resolve conflicting observations and clarify the relationship between deformation and metamorphism.

Timing of Gold Mineralization at Balmertown–Cochenour

Penczak and Mason (1997, 1999) have recently suggested that the Campbell gold deposit is analogous to "Cenozoic low sulphidation epithermal deposits" and that almost all of the alteration at the mine is related to "epithermal" gold mineralization. Penczak and Mason (1997, 1999) also state that gold mineralization at Red Lake is "clearly and unambiguously" constrained between 2720 ± 2 Ma and 2714 ± 4 Ma and that the deposit was deformed and metamorphosed during the Kenoran orogeny at 2650 Ma.

The date for the Kenoran orogeny in the Red Lake greenstone belt, quoted by Penczak and Mason (1997, 1999), is based on $^{40}Ar/^{39}Ar$ blocking ages for biotite and muscovite at the Goldcorp mine and hornblende in the Trout Lake batholith. Penczak and Mason (1998) state that the 2650 Ma age for peak Kenoran metamorphism in the Superior Province is based on U-Pb zircon ages from syntectonic granitoids across the Superior Province. Their assumption that the Kenoran orogeny affected the entire Superior Province at 2650 Ma is incorrect and inconsistent with the tectonic history of the Superior Province, the Uchi Subprovince and the Red Lake greenstone belt (Corfu 1987, 1988; Williams 1989; Stott and Corfu 1991; Card 1990; Williams et al. 1992; Stott 1997).

The Kenoran orogeny represents a major stage in the construction of the Superior Province when composite terranes converged and merged to form a single craton. In northwestern Ontario, the North Caribou terrane formed the core of a microcontinent to which younger Archean crust was added at episodic intervals. The Uchi Subprovince, which includes the Red Lake greenstone belt, was added to the southern flank of the North Caribou terrane and was deformed and intruded by numerous plutons during an inferred collision with other terranes from the south (Williams et al.1992). This episode of the Kenoran orogeny, known as the "Uchian phase", is estimated to have occurred in the Pickle Lake belt between 2713 Ma (the last period of volcanism in the Lake St. Joseph assemblage) and 2701 Ma (the last phase of significant granitoid emplacement)(Stott et al. 1989). In the Red Lake and Birch–Confederation greenstone belts, mapping by numerous geoscientists (see "References"), combined with U-Pb age determinations, has demonstrated that regional deformation, metamorphism and granitoid emplacement, associated with the "Uchian phase" of the Kenoran orogeny, are bracketed between ca. 2720 Ma and 2704 Ma (Percival et al. this volume). This time interval is the likely time of deformation and metamorphism of the Campbell and Goldcorp gold deposits. It should be noted that the "Uchian phase" predates the culmination of orogenesis in the southern part of the Superior Province, which occurred between 2689 and 2684 Ma (Corfu and Stott 1986).

The interpretation by Penczak and Mason (1997, 1999) that the Campbell mine is an "epithermal" gold deposit is debatable since the depositional environment for the gold mineralization at the Campbell mine is inconsistent with the majority of "epithermal" gold systems (Taylor 1995). The term "epithermal" describes high level mineralization that is coeval with volcanism and high-level (epizonal) plutonism (Gebre-Mariam, Hagemann and Groves 1995). The Campbell and Goldcorp deposits are situated within an assemblage of plume-related, mafic to ultramafic, tholeiitic to komatiitic, metavolcanic rocks interlayered with only minor intermediate to felsic metavolcanic lithologies (*see* "Background"). The komatiite–tholeiite may have been erupted in a shallow submarine continental margin setting (Tomlinson et al. 1998; Hollings, Wyman and Kerrich 1999). Epithermal gold deposits rarely occur in mafic and ultramafic metavolcanic rocks (White and Hedenquist 1990; Taylor 1995). White and Hedenquist (1990) state that, "in the rare cases where basic volcanics host epithermal deposits, the volcanics commonly have shoshonitic or alkaline affinities" which is not the case at the Campbell and Goldcorp mines. The majority of the examples of epithermal deposits that Penczak and Mason (1997, 1999) compare to the Campbell deposit are hosted by central to proximal, intermediate to felsic pyroclastic rocks and clastic sedimentary rocks. According to Penczak and Mason (1997) the Campbell mine shares features that are similar to everything from hot springs to Carlin-type deposits.

Penczak and Mason (1997, 1999) have not identified any potential synvolcanic or high-level intrusions that may have served as a heat and fluid source for an extensive epithermal system. If the gold mineralizing event is "clearly and unambiguously" constrained between 2720 ± 2 Ma and 2714 ± 4 Ma—as stated by Penczak and Mason (1997)—then a synvolcanic intrusion could not have been involved in the gold mineralizing event. Volcanism in the Balmer assemblage was finished by 2964 Ma and had terminated in the Red Lake greenstone belt by 2730 Ma (Corfu and Wallace 1986; Corfu and Andrews 1987; Stott and Corfu 1991; Parker 1999b; Sanborn-Barrie et al. 2000; Sanborn-Barrie, Skulski and Parker in press; Rogers et al. 2000).

The gold deposits in the Balmertown–Cochenour area have features similar to "epithermal" styles of mineralization such as 1) dominant brittle deformation and extension; 2) evidence for several stages of hydrothermal activity and brecciation; 3) abundant open-space filling textures such as "jig-saw breccia" veins and colloform, cockade and crustiform textures in ferroan-dolomite veins. However, these deposits also include features similar to deeper level "mesothermal" deposits such as 1) late emplacement of gold relative to the development and history of the greenstone belt; 2) similar structural timing and alteration styles to other gold deposits in the Red Lake camp and in other gold camps in Ontario (Colvine et al. 1988; Fyon et al. 1992); 3) the presence of deeply sourced mineralizing fluids (Andrews et al. 1986; Colvine et al. 1988); 4) greenschist and amphibolite-facies host rocks. The Campbell and Goldcorp deposits may represent shallow-level Archean lode-gold deposits which Gebre-Mariam, Hagemann and Groves (1995) suggest are upper crustal equivalents to deeper "mesothermal" deposits.

Fluid inclusion studies at the Campbell mine indicate that auriferous fluids had pressures of ~3 kbar (Tarnocai and Hattori 1996). The fluid pressures are comparable to lithostatic pressures (2 to 3 kbar) estimated from plagioclase-garnet-andalusite-quartz geobarometry and metamorphic assemblages (Tarnocai and Hattori 1996). Christie (1986) reported pressure and temperature estimates of 3 to 4 kbar and 440 to 510°C at the Campbell mine. Pressure and temperature estimates at the Goldcorp mine (Mathieson 1982) show that metamorphic mineral assemblages record temperatures of 520 to 540°C and fluid pressures of 3.8 to 4.2 kbar. Temperatures indicated by the arsenopyrite geothermometer are in the range 500 to 530° C (Mathieson 1982). Damer (1987) reported pressure and temperature estimates of 1.4 to 2 kbar and 435 to 550°C at the Goldcorp mine. Using the classification scheme proposed by Gebre-Mariam, Hagemann and Groves (1995) the gold deposits in the Balmertown–Cochenour area can be classified as "mesozonal" (300 to 475°C; 1.5 to 3 kbar; 6 to 12 km) to "hypozonal" (475 to 700°C; 3 to 6 kbar; >12 km).

Gold occurrences and associated alteration are located in 1) all of the supracrustal assemblages in the Red Lake greenstone belt; and 2) in intrusive rocks such as the Dome and McKenzie stocks emplaced at about 2720 Ma and the Wilmar dike at 2701 ± 1.5 Ma (Corfu and Andrews 1987). The author concurs with Andrews et al. (1986) that the majority of gold mineralization in the Balmertown–Cochenour area was deposited relatively late in the tectonic history of the greenstone belt. The most significant carbonate alteration occurred during the early stages of D_2 deformation (about 2718 Ma) but also continued throughout the deformation event. There is evidence at East Bay on Red Lake that some ferroan-dolomite veins were emplaced in pre-existing D_1 structures or were emplaced during D_1. Significant syntectonic to late tectonic gold mineralizing events postdate most of the carbonate and potassic alteration. The alteration was also overprinted by amphibolite-facies contact metamorphism. Metamorphic textures indicate that porphyroblastic minerals crystallized syn- to post-D_2 and may have been coeval with some gold mineralizing events. These relationships indicate that alteration and subsequent gold mineralization in the Balmertown–Cochenour area occurred from about 2720 Ma (age of the McKenzie and Dome stocks) until 2699 Ma (age of the Walsh Lake pluton) based on regional, relative timing relationships between alteration, deformation and contact metamorphism described in this summary.

RECOMMENDATIONS FOR GOLD EXPLORATION

The recognition of high temperature calc-silicate skarn assemblages in carbonatized mafic metavolcanic rocks along the margins of the Killala–Baird batholith and Walsh Lake pluton suggests that these areas may have the potential to host disseminated-replacement style gold mineralization similar to the Madsen mine.

Regional distribution of gold mineralization and associated alteration indicates that proximal ferroan-dolomite alteration zones, accompanied by intense potassic metasomatism, are prime targets for gold exploration. The proximal alteration zones described below should be reassessed for their gold potential.

1. The large area of ferroan-dolomite alteration centered on Middle Bay at the west end of the greenstone belt (Parker 1999a) encompasses numerous gold occurrences and small past-producing mines and includes: intense ferroan-dolomite altered mafic and ultramafic rocks; thick ferroan-dolomite veins (Parker 1999a); and sericitized (potassic alteration) intermediate to felsic metavolcanic rocks. This proximal alteration zone extends along the south limb of the Pipestone Bay anticline (Riley 1975).
2. The proximal ferroan-dolomite zone north of Madsen is an important gold exploration target that encompasses several gold prospects. Intense ferroan-dolomite alteration occurs throughout this area and is accompanied by very thick ferroan-dolomite extension veins; areas of pervasive silicification; strong tourmaline alteration and potassic metasomatism in the form of biotite and sericite. Some gold deposits within this area, such as the Redruth and Paulore prospects, occur in amphibolitized mafic metavolcanic rocks.

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23. Project Unit 98-002. Nickel-Copper-Platinum Group Element Sulphide Mineralization in the Red Lake Greenstone Belt: A Preliminary Report

J.R. Parker[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

This summary presents results for a project conducted in conjunction with the Western Superior NATMAP program. The project was initiated to study the distribution of nickel-copper-platinum group element sulphide mineralization in the Red Lake greenstone belt as part of a broader effort to study the regional metallogeny of the northwestern Superior Province. This component of the project to-date has consisted of reconnaissance sampling and mapping of mafic and ultramafic intrusive rocks in the Red Lake greenstone belt and surrounding areas.

The discovery of significant palladium and nickel values in the Red Lake greenstone belt was announced earlier this year (Rubicon Minerals Corp., News Release, June 6, 2000; Goldcorp Inc., News Release, July 10, 2000). This has stimulated some exploration for platinum group metals in the belt.

Unless otherwise noted, all data presented in this report were provided by the Geoscience Laboratories, Ontario Geoservices Centre, Sudbury.

DISTRIBUTION OF MAFIC AND ULTRAMAFIC INTRUSIVE ROCKS

The reader is referred to Parker (this volume) for a description of the general geology and tectonic history of the Red Lake greenstone belt.

Mafic and ultramafic intrusive rocks commonly consist of medium- to coarse-grained, massive, dark green gabbro, peridotite and pyroxenite. Large, composite, peridotite-pyroxenite ± gabbro intrusions (Figure 23.1) are located at: 1) Pipestone Bay and Golden Arm and intrude Ball assemblage (2940 ± 2 Ma and 2925 ± 3 Ma) (Corfu and Wallace 1986) supracrustal rocks (Riley 1975, 1978a, 1978b); and 2) at East Bay, Balmer Lake and Golden Arm where they intrude Balmer assemblage (2922 +20/-9 Ma, 2989 ± 3 Ma and 2965 +5/-1 Ma) (Corfu and Andrews 1987) supracrustal rocks (Riley 1975; Pirie and Grant 1978a, 1978b). Some compositional layering is present in the ultramafic intrusion on the west shore of Golden Arm. Smaller gabbro and peridotite intrusions are located in the Balmer assemblage where they occur as sill-like bodies that are concordant or slightly discordant to stratigraphy and are probably synvolcanic to mafic and ultramafic metavolcanic flows. Gabbro intrusions are also located in the Slate Bay and Hoyles Bay areas where they intrude clastic metasedimentary rocks (Pirie and Sawitzky 1977) of the Slate Bay assemblage (2916 Ma) (Corfu et al. 1998). A variety of mafic and ultramafic rocks intrude metasedimentary rocks (Riley 1976) in the Trout Bay assemblage (2853 ± 1 Ma) (T. Skulski, Geological Survey of Canada, personal communication, 2000) at the west end of the greenstone belt. Medium-grained, massive gabbros intrude Confederation assemblage (~2740 Ma) rocks in the southeast portion of

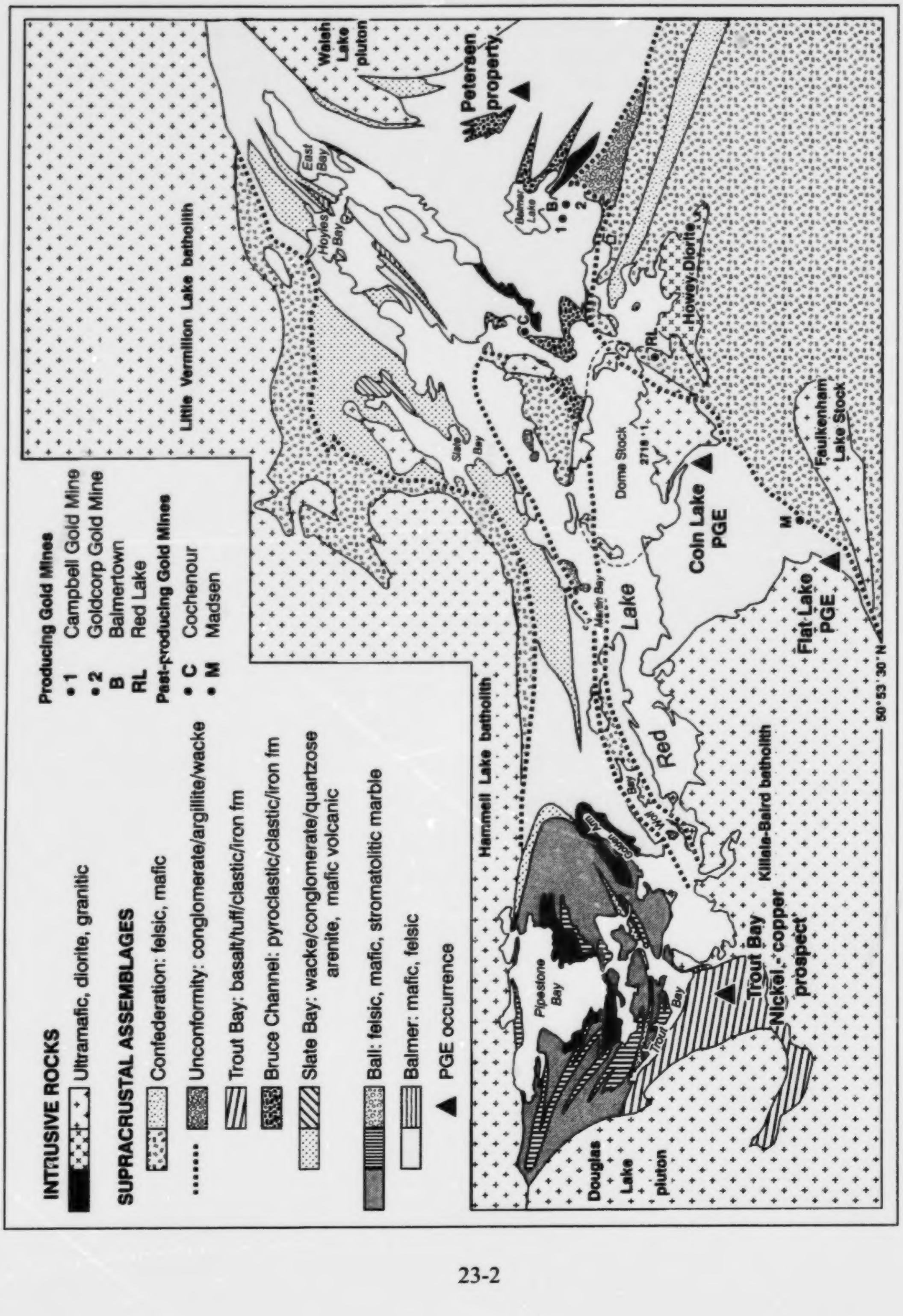

Figure 23.1. General geology of the Red Lake greenstone belt; distribution of supracrustal assemblages; and location of platinum group element sulphide mineralization (modified after Sanborn-Barrie, Skulski and Parker in press).

the greenstone belt. The majority of the mafic to ultramafic intrusions in the greenstone belt are variably carbonatized (calcite and ferroan-dolomite), serpentinized and talcose and affected by D_2 deformation. Therefore, the majority of these intrusions were probably emplaced prior to 2720 Ma (*see* Parker, this volume). A "quartz gabbro" (known locally as the "Campbell" or "Dickenson" diorite) has been dated at 2870 ± 15 Ma (Corfu and Andrews 1987), however, the "quartz gabbro" is very intensely altered and may be a supracrustal rock.

Several mafic-ultramafic intrusions are associated with granitoid rocks external to the Red Lake greenstone belt. These intrusions include the Hammell Lake anorthosite complex (Riley 1978b; Muir 1972) and a large body of hornblende amphibolite (metamorphosed gabbro) due east of Little Vermilion Lake (Atkinson and Stone 1993).

PALLADIUM-PLATINUM OCCURRENCES

Rubicon Minerals Inc. — Petersen Property, Balmer Township

In June of this year, Rubicon Minerals Inc. announced (Rubicon Minerals Corp., News Release, June 6, 2000) that they had obtained values of 1155 ppb Pd and 175 ppb Pt from a fine-grained mafic dike, and 256 ppb Pd and 180 ppb Pt from a unit of chert-magnetite iron formation. The dike and iron formation were intersected in during a diamond-drill program on the Petersen gold property in the Balmer assemblage (*see* Figure 23.1). No other information was given about the occurrence.

Goldcorp Inc. — Trout Bay Occurrence, Mulcahy Township

Goldcorp Inc. announced the discovery of significant palladium, platinum and nickel values from their Trout Bay property at the west end of Red Lake in the Trout Bay assemblage, Mulcahy Township (*see* Figure 23.1). The best reported value was 7.07 grams per tonne Pd and 7.08% Ni. Other values such as: 2.17 grams per tonne Pd and 1.32% Ni; 5.95 grams per tonne Pd and 4.52% Ni; and 6.06 grams per tonne Pd and 5.31% Ni were reported. Platinum values range between 0.14 and 1.46 grams per tonne Pt (Goldcorp Inc., News Release, July 10, 2000). This area hosts the Trout Bay nickel-copper prospect that was discovered by Cochenour–Willans Gold Mines Ltd. in 1956 (Riley 1968). The property has been explored by various companies over the years including INCO Exploration and Technical Services Inc. in 1992.

GENERAL GEOLOGY

The Trout Bay region (Figure 23.2) is underlain by an east- to northeast-facing, northwest-striking, folded sequence of fine-grained metasedimentary rocks consisting of argillite, wacke and siltstone. The metasedimentary rocks are overlain, in the east, by northeast-facing, mafic metavolcanic flows (*see* Figure 23.2) (Riley 1976). The metasedimentary rocks are separated from the mafic metavolcanic rocks by a heterolithic, mafic, tuff breccia previously mapped as conglomerate (Riley 1976). Metasedimentary rocks are interlayered with very minor, intermediate tuff and lapilli tuff breccia and quartz-magnetite iron formation (*see* Figure 23.2) (Riley 1976). The rocks have been metamorphosed to upper greenschist and amphibolite facies. The metasedimentary rocks are intruded by metamorphosed, mafic and ultramafic intrusions with variable amounts of garnet and amphibole porphyroblasts. The gabbro consists of massive, fine- to coarse-grained gabbro, leucogabbro and feldspar porphyritic gabbro. Anorthositic

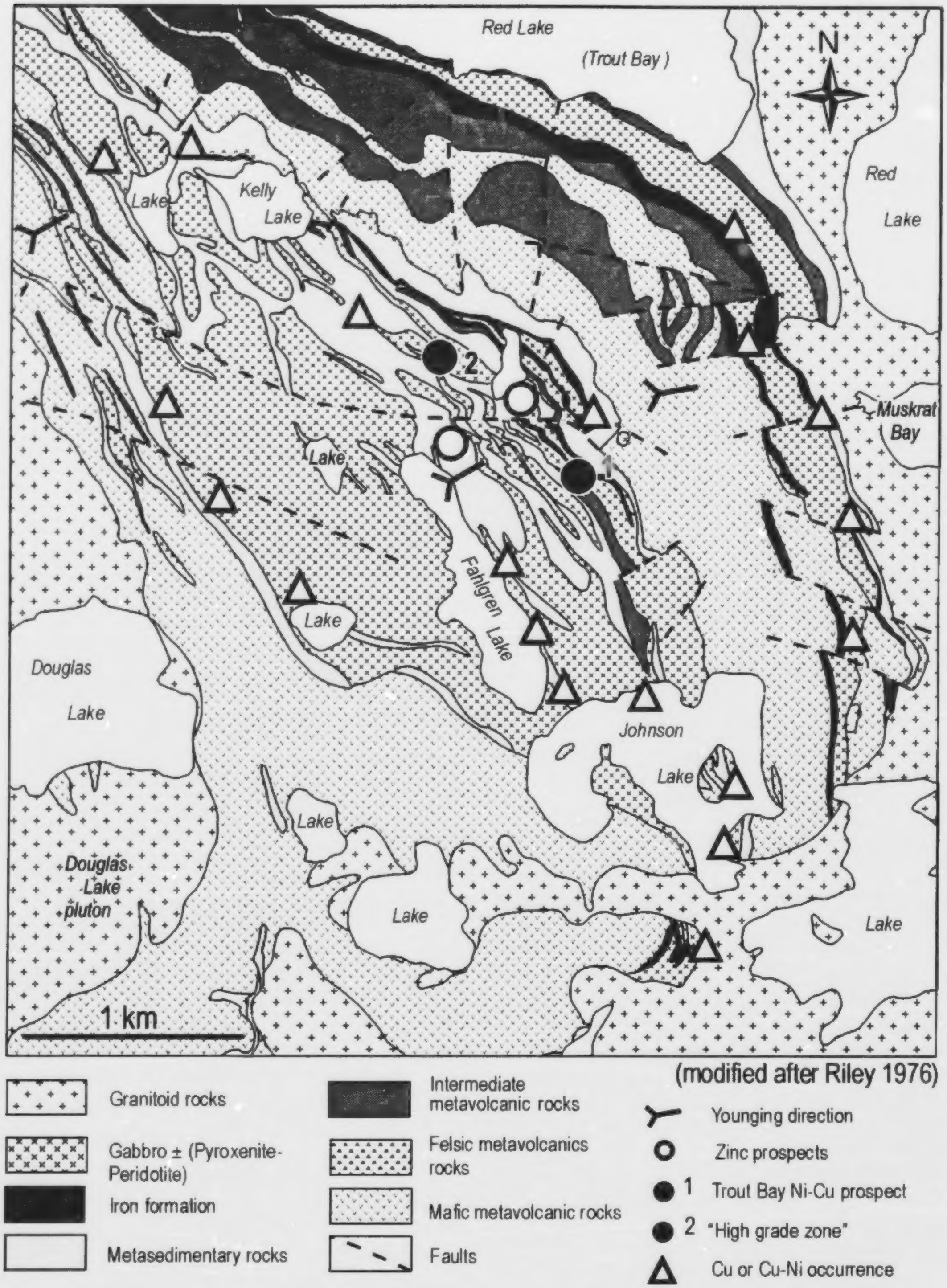

Figure 23.2. General geology of the Trout Bay area and location of copper or nickel-copper ± platinum group element sulphide mineralization.

gabbro is situated along the southwest shore of Trout Bay on Red Lake. A large gabbroic sill at Fahlgren Lake (*see* Figure 23.2) hosts numerous small nickel-copper occurrences. The metasedimentary rocks also host zinc-rich, volcanogenic massive sulphide mineralization intruded by gabbro sills or dikes (Parker 1999; *see* Figure 23.2).

The metasedimentary-metavolcanic rocks at Trout Bay were originally correlated with Balmer-age rocks (i.e., 3000 to 2900 million years old) (Stott and Corfu 1991), however, a preliminary radiometric age of 2853 ± 1 Ma was recently determined from zircons in a dacitic tuff interlayered with metasedimentary rocks (T. Skulski, Geological Survey of Canada, personal communication, 2000). Northeast-facing, mafic and intermediate metavolcanic flows (Riley 1976) that overlie the metasedimentary rocks are intruded by an intermediate porphyry dike with an U-Pb zircon age of 2735 ± 1 Ma (T. Skulski, Geological Survey of Canada, personal communication, 2000). Therefore, the mafic metavolcanic rocks were extruded prior to 2735 Ma and may be similar in age to the underlying metasedimentary and metavolcanic rocks. This sequence of supracrustal rocks is presently referred to as the Trout Bay assemblage (Sanborn-Barrie, Skulski and Parker in press). Mafic and ultramafic rocks postdate supracrustal rocks in the Trout Bay assemblage.

Deformation in the Trout Bay area is characterized by complex refolded folds in local areas. The earliest recognized deformation (D_1) consists of north-trending, shallow-plunging, F_1 S-folds with an associated axial planar foliation. The F_1 folds are overprinted by shallow-plunging, west-striking, F_2 S-folds with an axial planar foliation developed during D_2. The mafic and ultramafic intrusive rocks have been affected by D_1 and D_2 fabrics.

MINERALIZATION

Kuryliw (1963) and Riley (1976) indicate that a composite mafic to ultramafic sill hosts the Trout Bay nickel-copper prospect (*see* Figure 23.2). This sill contains a section of porphyritic to glomeroporphyritic gabbro, with white feldspar phenocrysts up to 5 cm in size, that can be traced along the length of the sill. The contacts of the sill are bounded by chert-magnetite iron formation. Kuryliw (1963) reported that nickel-copper sulphide mineralization was concentrated at the base of the sill near a contact with chert-magnetite iron formation. The mineralized zone is 122 m long and 10 m wide with an approximate grade of 0.5% nickel and 0.25% copper (Shklanka 1969). Semi-massive chalcopyrite, pyrrhotite, pyrite and pentlandite is hosted in a tremolite-antigorite-magnetite schist (Kuryliw 1963) at the base of the sill. Sulphide mineralization is strongly deformed and consists of 1) small elongate lenses and narrow layers parallel to foliation; and 2) sulphide-filled extension fractures that transect foliation. Chalcopyrite halos enclose pentlandite-rich lenses in altered host rocks (Shklanka 1969). Kuryliw (1963) also described a unit of "ultramafic amphibolite schist" located between units of chert-magnetite iron formation. The schist is dominantly composed of serpentine-amphibole and contains sulphide minerals in teardrop-shaped lenses and in bands on foliation planes (Kuryliw 1963).

Recent power stripping at the Trout Bay nickel-copper prospect has exposed a coarse-grained ultramafic rock that intrudes a thick sequence of chert-magnetite iron formation. The ultramafic rocks are pale green, fine grained and strongly altered to talcose, serpentine-tremolite schist along the contact with iron formation. The ultramafic rock contains abundant xenoliths of iron formation, but some of the chert appears to have been leached from the xenoliths leaving remnant blobs of coarse, recrystallized magnetite. The altered rock contains about 3% disseminated sulphide minerals consisting of chalcopyrite, pyrite and pyrrhotite. The intrusion consists of relatively unaltered, coarse-grained pyroxenite about 8 m from the contact.

Power stripping at the "high grade zone" (*see* Figure 23.2)—on Kuryliw's "ultramafic amphibolite schist" unit—has revealed a strongly altered and schistose ultramafic rock intruding chert-magnetite iron formation. The altered ultramafic rock grades into relatively unaltered, coarse-grained pyroxenite. The contact with the iron formation is garnetiferous and contains about 1% disseminated chalcopyrite. A poorly exposed unit of tremolite schist consisting of semi-massive, fine-grained, pyrrhotite, pentlandite and chalcopyrite is known as the "high grade zone" where palladium values of 7.07 and 7.53 grams per tonne have been reported (Goldcorp Inc., News Release, July 10, 2000).

Numerous small nickel-copper occurrences are hosted by a large fine- to coarse-grained gabbro intrusion at Fahlgren and Johnson lakes (*see* Figure 23.2). The majority of the occurrences are hosted by coarse-grained gabbro that has been variably altered. Some large sections of the gabbros have been uralitized and altered to fine-grained, pale green actinolite (Kuryliw 1963). The gabbros host fine-grained, disseminated chalcopyrite and pyrrhotite or irregular blebs of sulphide minerals up to 3 cm.

The author sampled several nickel-copper occurrences in the gabbro at Fahlgren Lake as well as poorly exposed pits at the Trout Bay nickel-copper prospect and "high grade zone" in 1998 and 1999. Analyses of these samples are presented in Table 23.1. Analyses for samples from the newly stripped areas were unavailable at the time of writing. High palladium values appear to correspond with high nickel values (Goldcorp Inc., News Release, July 10, 2000) although the data in Table 23.1 indicate that elevated copper values also correspond with some elevated palladium values. Semi-massive, zinc-rich, volcanogenic sulphide mineralization in the area also contains erratic, elevated, palladium values (128 ppb) (*see* Table 23.1). A significant geochemical characteristic of the sulphide mineralization, hosted by mafic and ultramafic rocks, is extreme, fractionated Pd/Pt ratios (as high as 20 and 74) and Pd/Cu ratios (0.01–0.74). Peach and Mathez (1996) have shown that extreme Pd/Pt and Pd/Cu ratios are probably the result of hydrothermal modification that postdates initial sulphide mineral deposition. This interpretation is consistent with observed alteration and deformation in the mafic and ultramafic intrusive rocks.

LITHOGEOCHEMISTRY

Chondrite-normalized rare earth element (REE) patterns (Figures 23.3 and 23.4) for basalts—located northeast of the metasedimentary rocks at Trout Bay—are flat, 3 to 4 times chondrite and slightly depleted in the light REE with $(La/Yb)_N$ ratios between 0.77 and 0.90. Chondrite-normalized trace element patterns for the basalts show no enrichment in Th and Nb with patterns that are less than 2 to 3 times chondrite. The trace element patterns are similar to those for normal mid-ocean ridge tholeiitic basalts (N-MORB) (Sun and McDonough 1989) with no evidence for assimilation of crustal material.

Chondrite-normalized rare earth element (REE) patterns (*see* Figures 23.3 and 23.4) for gabbro—at Fahlgren Lake and in the vicinity of the zinc showings at Trout Bay—are also relatively flat, 3 to 10 times chondrite and slightly depleted in the light REE with $(La/Yb)_N$ ratios between 0.84 and 1.19. Chondrite-normalized trace element patterns for gabbros show weak enrichment in Th and Nb with the exception of one sample (*see* Figure 23.4). This weak enrichment may indicate that the gabbros were contaminated by the assimilation of some crustal material. Some representative geochemical analyses for the gabbro are listed in Table 23.2. The similarities in the geochemistry of the basalt and the gabbro suggests that the gabbro may represent synvolcanic intrusions.

Table 23.1. Assay data for magmatic Ni-Cu-PGE and volcanogenic Zn-Cu sulphide occurrences, Trout Bay, Red Lake greenstone belt and for samples taken at other locations in the Red Lake belt as well as from Setting Net Lake in the Favourable Lake greenstone belt.

Sample	Rock Name	Description	Co ppm	Cu ppm	Ni ppm	Cr ppm	Pt ppb	Pd ppb	As ppm	Zn ppm	Ag ppm	Au ppb	Pd/Pt
TROUT BAY, RED LAKE													
9295A	cg gabbro	pyrrhotite blebs (1.5 cm)	71	350	675	402	22.24	89.40	N.D.	90	4	N.D.	4.02
9298A	mg gabbro	no visible sulphide minerals	44	48	184	>500	N.D.	N.D.	N.D.	101	4	N.D.	—
9300	mg gabbro	~5% disseminated po, cp	63	554	92	39	9.71	6.62	N.D.	103	4	8	0.68
9311	mg gabbro	10% po, cp blebs	80	844	462	332	15.19	50.03	N.D.	117	4	6	3.29
9313	cg gabbro	25% po, cp	134	485	1546	306	25.55	193.72	37.58	143	4	17	7.58
9315A	cg gabbro	0-25% po, cp, py	75	634	54	25	N.D.	N.D.	18.8	138	4	11	—
9315B	cg gabbro	0-25% po, cp, py	51	167	67	43	17.19	15.62	25.94	118	4	13	0.91
9320B	fg gabbro	no visible sulphide minerals	49	18	209	369	N.D.	7.6	N.D.	87	4	N.D.	
9352A	tremolite schist	no visible sulphide minerals	47	107	167	356	7.96	8.43	N.D.	105	4	N.D.	1.06
9356A	cg gabbro	5-25% disseminated po, cp	46	68	287	>500	N.D.	8.74	5.78	103	4	N.D.	—
9356B	cg alt. gabbro	5-25% disseminated po, cp	28	1135	1025	444	43.63	145.22	44.73	128	4	6	3.33
9366A	mg gabbro	round blebs of po, cp	165	4242	2440	>500	50.54	356.42	9.85	124	4	28	7.05
9638B*	tremolite schist	minor po	30	680	961	N.A.	176.75	506.12	9.33	111	5	37	2.86
9638A*	tremolite schist	15% po	10	134	129	N.A.	N.D.	9.14	N.A.	98	1	54	—
9638C*	tremolite schist	25% po, py, cp	406	3950	23770	N.A.	112.50	1781.87	N.A.	N.D.	4	65	15.84
8A	fg gabbro	minor po	66	2085	2507	N.A.	112.53	533.76	N.D.	122	4	49	4.74
11L**	mass. sulphides	po, cp, sp	836	1373	145	N.A.	19.39	128.47	1015	61716	42	163	6.63
11P**	mass sulphides	po, cp	1333	9817	105	N.A.	9.92	13.24	1819	60671	50	330	1.33
11R**	tremolite schist	5% pyrrhotite blebs	59	2071	85	N.A.	7.16	16.84	N.D.	28685	19	46	2.35
OTHER AREAS IN THE RED LAKE BELT (see text for more information)													
9827	ultramafic flow	5% sulphide minerals	31	40	163	N.A.	90.07	1245.90	N.A.	109	2	36.0	13.83
9837A	ultramafic flow	No visible sulphide minerals	66	51	821	N.A.	52.40	2758.3	N.A.	79	3	N.D.	52.64
SETTING NET LAKE													
100	mafic mv flows	disseminated po	27	115	122	N.A.	36.95	336.79	96	197	2	13	9.11
102A	mafic mv flows	disseminated po, cp	38	343	69	N.A.	16.46	167.98	N.D.	175	4	39	10.21
103	chert	disseminated po	N.D.	31	8	N.A.	8.24	165.05	8.47	48	N.D	6	20.02

All geochemical analyses provided by the Geoscience Laboratories, Ontario Geoservices Centre, Sudbury. * Samples from the "High Grade zone" area. ** Samples taken from zinc occurrences. Abbreviations: alt – altered; cg – coarse-grained; cp – chalcopyrite; fg – fine-grained; mass – massive; mg – medium-grained; mv – metavolcanic; N.A. – not available; N.D. – not detected; po – pyrrhotite; py – pyrite; sp – sphalerite.

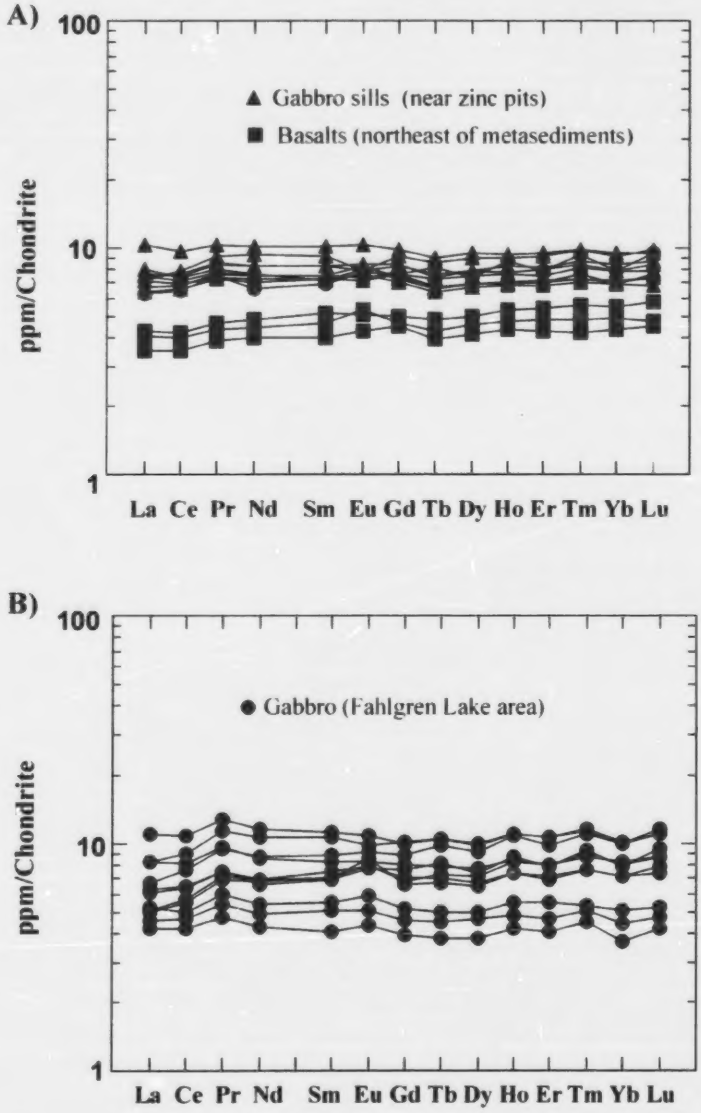

Figure 23.3. Chondrite-normalized rare earth element patterns for A) pillowed basalts northeast of the metasedimentary sequence at Trout Bay and gabbro sills adjacent to volcanogenic massive sulphide zones; B) gabbro from the Fahlgren Lake area (*see* Figure 23.2). Normalizing values for chondrite from Taylor and McLennan (1985).

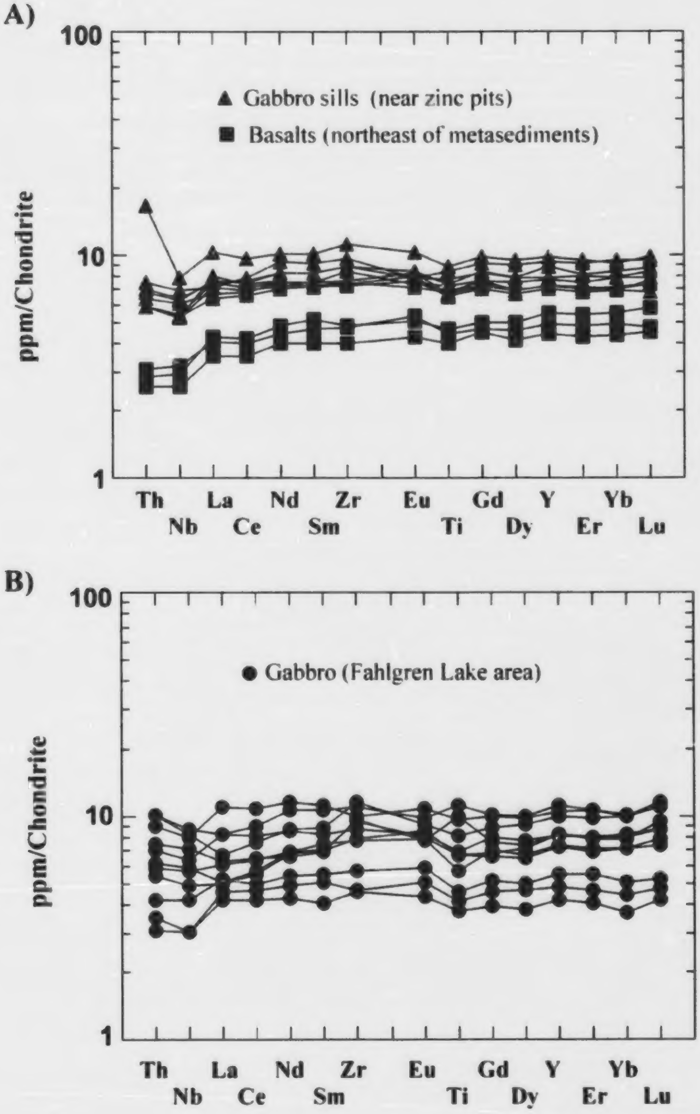

Figure 23.4. Chondrite-normalized trace element patterns for A) pillowed basalts northeast of the metasedimentary sequence at Trout Bay and gabbro sills adjacent to volcanogenic massive sulphide zones; B) gabbro from the Fahlgren Lake area (*see* Figure 23.2). Normalizing values for chondrite from Taylor and McLennan (1985).

Table 23.2. Selected geochemical analyses of representative gabbro (Fahlgren Lake) and mafic metavolcanic rocks from the Trout Bay assemblage, Red Lake greenstone belt.

	9298A	9311	9313	9315A	9315B	9295A	9352A	9638B	1	2
	gab	**gab**	**gab**	**gab**	**gab**	**gab**	**tscht**	**gab**	**bas**	**bas**
SiO_2 %	47.56	46.65	44.94	50.54	50.42	46.37	48.48	50.65	49.46	47.17
Al_2O_3	18.45	19.74	15.67	11.87	13.72	17.01	16.06	19.51	15.89	17.29
MnO	0.14	0.15	0.20	0.26	0.22	0.15	0.18	0.41	0.18	0.17
MgO	9.45	6.30	9.03	4.49	6.11	8.94	8.99	4.14	8.93	10.87
CaO	12.14	10.28	9.61	9.11	10.25	11.29	10.91	7.08	11.67	11.34
Na_2O	1.57	1.94	1.39	1.54	2.09	1.57	1.77	2.30	2.03	1.18
K_2O	0.15	0.19	0.12	0.19	0.19	0.25	0.14	0.73	0.1	0.16
P_2O_5	0.03	0.05	0.01	0.24	0.08	0.05	0.06	0.03	0.04	0.05
TiO_2	0.41	0.62	0.73	1.66	1.05	0.73	0.75	0.51	0.51	0.44
Fe_2O_3	9.42	12.85	16.98	19.02	15.68	12.14	11.96	14.34	10.78	10.08
CO_2	0.18	0.12	0.13	0.27	0.29	0.09	0.16	0.24	0.08	0.04
LOI	1.11	1.61	1.98	1.38	0.81	1.23	1.08	0.99	0.55	1.52
S	0.01	1.35	2.24	1.93	0.15	0.64	0.03	0.14	0.05	0.01
Total	100.4	100.4	100.6	100.3	100.6	99.7	100.4	100.7	100.1	100.3
Mg#	67	49	51	32	44	59	60	40	62	68
Rb ppm	2.25	1.91	1.14	1.70	1.79	3.93	2.98	3.77	0.83	5.55
Ba	19	76	28	29	35	38	18	40	17	18
Sr	87	177.9	116.3	99.8	120.7	109.9	127.3	37.3	107.2	106.6
Sc	22	22	25	38	38	26	31	16	38	28
La	1.55	1.86	1.82	13.38	4.00	2.23	3.02	0.94	1.55	1.35
Ce	4.05	5.46	5.22	29.21	10.34	6.07	7.81	2.12	3.96	3.51
Nd	3.04	4.93	4.81	18.36	8.25	4.95	6.13	1.31	3.27	2.82
Sm	0.94	1.74	1.63	4.81	2.57	1.63	1.92	0.48	1.10	0.94
Eu	0.38	0.68	0.70	1.62	0.94	0.75	0.72	0.21	0.44	0.39
Gd	1.21	2.14	2.08	5.38	3.02	2.02	2.46	0.58	1.49	1.24
Tb	0.22	0.41	0.42	1.03	0.60	0.39	0.46	0.08	0.28	0.23
Yb	0.92	1.77	2.04	4.00	2.45	1.77	2.00	0.50	1.35	1.00
Lu	0.16	0.30	0.33	0.65	0.42	0.28	0.33	0.08	0.20	0.16
Y	9.51	16.72	18.74	35.91	23.39	16.43	18.45	5.23	12.72	10.49
Zr	25.40	43.24	52.37	81.03	54.86	43.67	48.18	14.74	25	25
Th	0.15	0.26	0.23	0.59	0.59	0.25	0.30	0.11	0.12	0.12
U	0.05	0.08	0.06	0.17	0.11	0.08	0.05	0.04	0.03	0.03
Hf	0.77	1.33	1.63	2.75	1.81	1.39	1.56	0.40	0.51	0.44
Nb	1.13	2.20	1.83	5.05	3.00	2.13	2.38	0.47	1.14	1.03
Ta	0.10	0.17	0.18	0.34	0.22	0.16	0.18	0.08	0.12	0.11
Cu	48	844	485	634	167	350	107	680	100	42
Ni	184	462	1546	54	67	675	167	961	151	237
Pt ppb	N.D.	15.19	25.55	N.D.	17.19	22.24	7.96	177	N.A.	N.A.
Pd	N.D.	50.03	193.7	N.D.	15.62	89.40	8.43	506	N.A.	N.A.

LOI = loss on ignition; **bas** = basalt; **gab** = gabbro; **N.A.**= not available; **N.D.** = not detected; **tscht** = tremolite schist.
Mg# (magnesium number) = 100*(MgO[weight%]/molecular weight MgO)/((MgO[weight%]/molecular weight MgO) + (FeO*[weight%]/molecular weight FeO)).

Other Platinum Group Element Occurrences

Two occurrences were discovered by the author following recent reconnaissance sampling in the Red Lake greenstone belt. These are described below. The analyses reported below were not rechecked for accuracy at the time of writing.

COIN LAKE

A sample was collected from an outcrop on the north shore of Coin Lake in Heyson Township (UTM 438311E; 5650824N (NAD 27)). The analysis of this sample returned values of 1245.9 ppb Pd and 90.07 ppb Pt (*see* Table 23.1 and Figure 23.1). The sample contained about 5% disseminated pyrite and was collected from a small, poorly exposed test pit on the edge of the outcrop. The ultramafic host rock (flow?) is massive and fine-grained with a rubbly, buff gray-brown weathered surface and a dark green-gray fresh surface. The host rock is also calcite carbonatized and contains numerous folded, white quartz veinlets.

FLAT LAKE

A sample was collected from an outcrop on the southeast shore of Flat Lake in Baird Township (UTM 434050E; 5645506N (NAD 27)). The analysis of this sample returned values of 2758.3 ppb Pd and 52.4 ppb Pt (*see* Table 23.1 and Figure 23.1). The sample contained no visible sulphide minerals. The sample was collected from pillowed ultramafic metavolcanic flows. The flows dominantly consist of fibrous green actinolite with fine-grained biotite on foliation surfaces and some possible, fine-grained, disseminated tourmaline. The rocks are also variably magnetic.

SETTING NET LAKE (FAVOURABLE LAKE GREENSTONE BELT)

Samples 100, 102A and 103 (*see* Table 23.1) contain between 165 to 336 ppb Pd and 8 to 37 ppb Pt and were collected at Setting Net Lake in the Favourable Lake greenstone belt located north of Red Lake. These samples were collected from altered mafic-ultramafic metavolcanic rocks in contact with sulphidic chert. The mafic rocks are altered and contain variable amounts of disseminated pyrrhotite.

DISCUSSION

Limited sampling by the author appears to indicate that some mafic and ultramafic rocks at Trout Bay host nickel-copper-platinum group element sulphide mineralization at contacts with chert-magnetite iron formation. Kuryliw (1963) noted that the majority of the mineralization was located in the basal section of an intrusion at the Trout Bay nickel-copper prospect. The ultramafic rocks at the contact are altered, schistose and host numerous partially assimilated xenoliths of chert-magnetite. The author favours an intrusive origin for the mafic and ultramafic rocks, however, an extrusive origin may also be possible (M. Dehn, Goldcorp. Inc., personal communication, 2000).

Magmatic nickel-copper-platinum group element sulphide mineralization forms from the segregation and concentration of liquid sulphide droplets from mafic or ultramafic magma and the subsequent partitioning of chalcophile elements into the droplets from the silicate melt (Naldrett 1997). Ultramafic and mafic rocks derived from high temperature, sulphur-undersaturated magmas are enriched in chalcophile metals. Sulphur-undersaturated magma are produced by large degrees of partial melting of upper mantle source regions that were depleted in sulphur by earlier partial melting events (Keays 1995). If these magma assimilate sulphide-bearing supracrustal rocks, such as metasedimentary or metavolcanic rocks, then the interaction of the external sulphur with the chalcophile-enriched magma causes sulphur saturation and may result in the precipitation of significant nickel-copper-platinum group element sulphide mineralization (Keays 1995). Irvine (1975) has also shown that assimilation of SiO_2-rich supracrustal rocks by a mafic magma could lower the solubility of sulphur within the magma and initiate the partitioning of chalcophile elements (Naldrett and Lightfoot 1997).

The nickel-copper-platinum group element sulphide mineralization at Trout Bay appears to be associated with the contamination of a sulphur undersaturated, chalcophile-enriched, magma by xenoliths of chert-magnetite iron formation. The chert portion of the xenoliths appears to have been partially assimilated by the mafic-ultramafic magma. The assimilation of SiO_2-rich material, known as "felsification" (Naldrett 1997), may have initiated sulphur saturation and the partitioning of chalcophile elements into the sulphur. The chert-magnetite iron formation may also contain small quantities of sulphide minerals (i.e., pyrite) that were assimilated by the magma, however, sulphide minerals have not been recognized in the iron formation. Sulphide minerals are hosted by nearby argillaceous metasedimentary rocks and may have been a potential source of external sulphur. The sulphide mineralization was subsequently modified by deformation and hydrothermal alteration which may explain the high Pd/Pt and Pd/Cu ratios that characterize the mineralization.

Preliminary results of reconnaissance sampling, in the Red Lake and Favourable Lake greenstone belts, indicate that some ultramafic metavolcanic flows may have potential to host platinum group element sulphide mineralization. These may be similar to komatiitic-associated nickel-copper-platinum group element sulphide mineralization, however, more work must be done to characterize the mineralization and host rocks.

RECOMMENDATIONS FOR EXPLORATION

Mafic and ultramafic intrusions emplaced in sulphidic felsic metavolcanic rocks or clastic and chemical metasedimentary rocks, similar to those at Trout Bay, may be potential targets for platinum-palladium mineralization. The Red Lake greenstone belt is endowed with mafic and ultramafic intrusive rocks inside and outside the belt. Mafic and ultramafic rocks intrude clastic and chemical metasedimentary rocks at Pipestone Bay (Riley 1975), at Slate Bay (Pirie and Sawitzky 1977); in the Fisher Islands area and at Golden Arm (Riley 1978a, 1978b) and should be prospected for Ni-Cu-PGE sulphide mineralization.

Ultramafic flows, such as those sampled on Coin and Flat lakes, may also have potential to host platinum group element sulphide mineralization and should be prospected and sampled.

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24. Project Unit 98-016. Combined U-Pb Columbite and $^{40}Ar/^{39}Ar$ Mica Ages from Rare-Element Pegmatites, Superior Province of Northwestern Ontario

S.R. Smith[1], R.L. Romer[2], F.W. Breaks[3], S.P. Kelley[1] and A.G. Tindle[1]

[1] Department of Earth Sciences, The Open University, Milton Keynes, U.K.
[2] GeoForschungsZentrum Potsdam, Telegrafenburg, D-14473 Potsdam, Germany
[3] Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

We report the first U-Pb columbite-tantalite ages for rare-element pegmatites in the Superior Province. Columbite from a beryl-type and a complex-type, petalite-subtype pegmatite within the eastern subgroup of the Separation Rapids pegmatite group, located within the Bird River–Separation Lake belt yielded respective discordant upper intercept ages of 2649 ± 4 Ma and 2642 ± 8 Ma. These ages are indistinguishable from the 2646 ± 2 Ma U-Pb monazite age (Larbi et al. 1999) of the nearby Separation Rapids pluton. These data confirm the genetic links between this S-type peraluminous granite pluton and the eastern subgroup of the Separation Rapids pegmatite group. U-Pb columbite ages from the southwestern subgroup of the Separation Rapids pegmatites, also interpreted to be genetically linked with the Separation Rapids pluton, thus far have revealed younger apparent ages. Here, the "Big Mack" petalite pegmatite has a concordia age of 2603 ± 2.5 Ma, interpreted as the age of secondary replacement or post deformational recrystallization.

$^{40}Ar/^{39}Ar$ mica ages from rare-element pegmatites of the Superior Province have been affected by two Proterozoic events, a 2.4 Ga thermal resetting and an 1850 Ma partial disturbance of the Ar-Ar system.

Deformed dikes within the Pakeagama Lake pegmatites, located within the northwestern Superior Province, have $^{40}Ar/^{39}Ar$ mica ages of 2672 ± 3 Ma and 2679 ± 15 Ma. Tantalite from late-stage, amblygonite-quartz-lepidolite veins that crosscut the undeformed, quartz-spodumene core zone of the Pakeagama Lake pegmatite provides a best age estimate of 2645 ± 2 Ma.

BACKGROUND

As part of a continuing collaboration between The Open University and Ontario Geological Survey (Smith, Tindle and Breaks 1999; Smith et al. 1999), field and laboratory investigations bearing upon the geochronological history of rare-element pegmatites in the Superior Province have focussed on two areas of high economic potential (Figure 24.1):

- Separation Lake area
- Pakeagama Lake area.

The Separation Rapids pegmatite group, located 70 km north of Kenora, is hosted by mafic and minor felsic metavolcanic rocks and banded iron formation of the Separation Lake greenstone belt, that is described as an eastward extension of Bird River Subprovince (Blackburn and Young 1994, 2000). Rare-element pegmatites of beryl-type and complex-type, petalite-subtype are dominant (Breaks and Tindle 1997). The likely parent granite to the Separation Rapids pegmatites is the Separation Rapids pluton, 2646 ± 2 Ma (Larbi et al. 1996), an S-type peraluminous granite described by Pan and Breaks (1997) and Breaks and Tindle (1997).

Pan and Breaks (1997) interpreted a spatial and geochemical link between the Separation Rapids pluton and the Separation Rapids rare-element pegmatite group. Thus, this study tests this hypothesis using thermal ionization mass spectrometry (TIMS) for U-Pb age determinations of columbite-tantalite to determine if there is a temporal as well as a spatial and geochemical link. Increasingly, assumed parental granites have been found to be younger than the adjacent rare-element pegmatite fields, thereby precluding any genetic relationship, e.g., Romer and Smeds (1996). This relationship, however, may be based upon dating phases within the parental granites with a rather low closing temperature, thus yielding artificially low age estimates. This forms the impetus for the study of age links between the Separation Rapids rare-element pegmatites and the adjacent peraluminous Separation Rapids pluton using geochronologically robust phases.

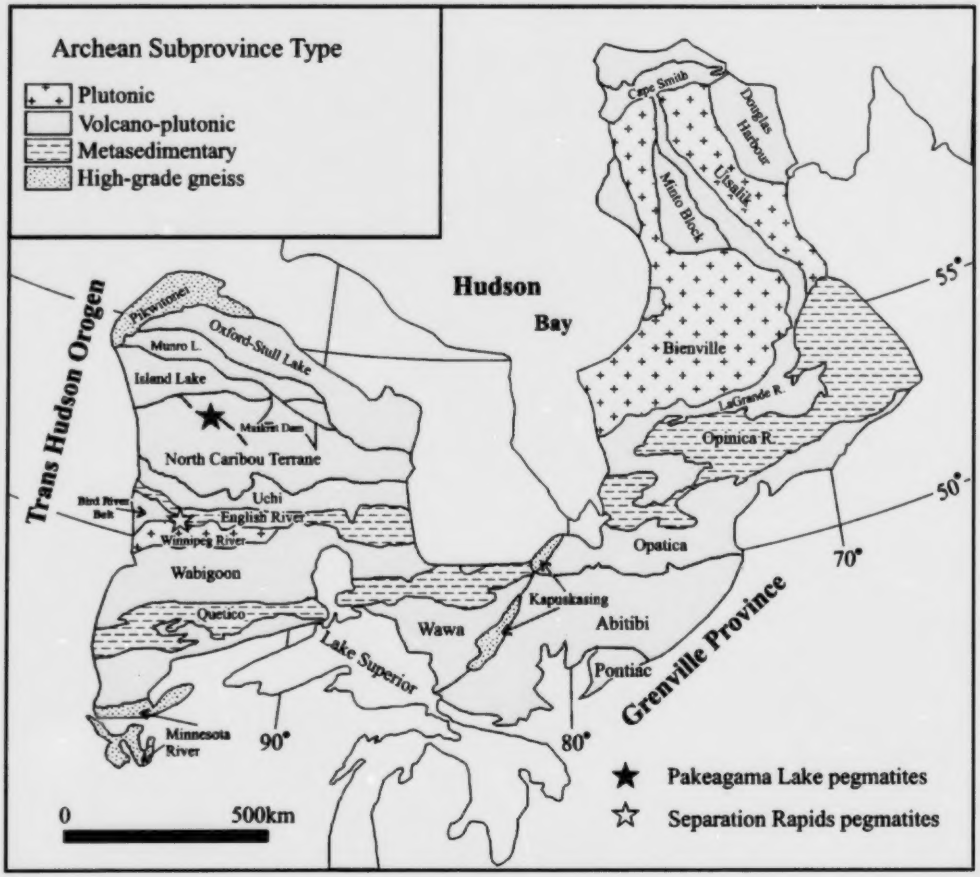

Figure 24.1. Location of the Separation Rapids pegmatites at the English River – Winnipeg River subprovincial boundary and the Pakeagama Lake pegmatites along the Bear Head fault zone, within the North Caribou terrane.

The Pakeagama Lake pegmatites are located approximately 200 km north of Red Lake within the North Caribou terrane, close to the Bear Head Lake fault zone delineated by Stone, Fogal and Fitzsimon (1993). The pegmatites are a series of complex-type, petalite-subtype pegmatite dikes with combined dimensions of up to 50 m width and an exposed strike length of 250 m. The dikes are undeformed to modestly affected by ductile deformation, steeply dipping, strongly zoned and contain five distinguishable units, mapped and described by Breaks et al. (1999). The pegmatites are partly in contact with banded ironstones and mafic metavolcanic rocks along the northwest periphery. However, most of the pegmatite is contained within a plausible parent granite, the Pakeagama Lake pluton, which is also a peraluminous S-type granite, moderately foliated and locally containing biotite, muscovite and garnet (Breaks, Tindle and Smith 1999).

U-Pb Geochronology

All U-Pb columbite analyses were performed at the GeoForschungsZentrum Potsdam following the procedure outlined in Romer and Smeds (1996). Columbite-tantalite minerals have been shown to be extremely useful in dating rare-element pegmatites, and the technique for analysis has been developed and refined over several years (Romer and Wright 1992; Romer, Smeds and Černý 1996). Columbite-tantalite minerals are Nb-Ta oxides that crystallize from highly chemically fractionated granitic melts and have been used by a number of workers (e.g., Černý et al. 1986; Tindle and Breaks 1998) to trace the degree of fractionation and internal evolution of rare-element granitic pegmatites. This is made possible by the continuous substitution of Fe-Mn and Nb-Ta during fractionation of the granitic melt.

Relatively large (1 to 5 mm) columbite-tantalite grains were initially "screened" using the Cameca SX100 electron microprobe facility at the Open University. Backscattered electron images were subsequently acquired, and spot analyses provided information on the variation in composition of grains (Figure 24.2). Grains containing obvious secondary Nb-Ta phases and alteration/replacement textures were generally avoided as these cannot be separated during the ion-exchange chemistry.

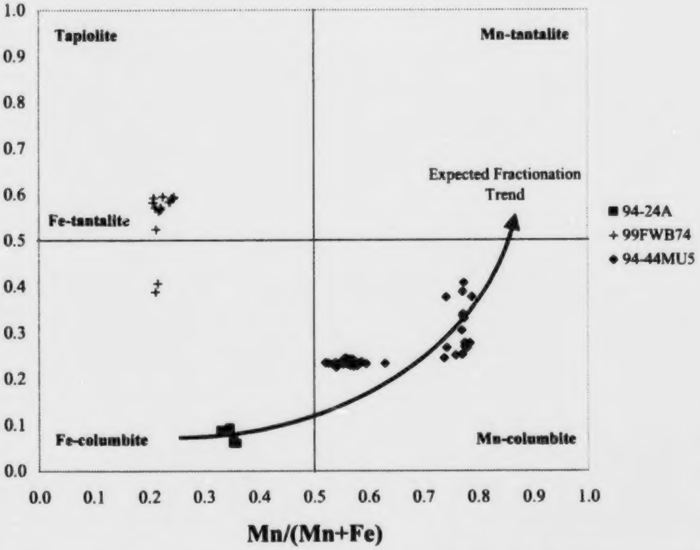

Figure 24.2. Columbite-tantalite quadrilateral showing the composition of grains used for U-Pb geochronology. Note the deviation of sample 99FWB74 from the expected fractionation trend within the Separation Rapids pegmatites. Such compositions are created by secondary alteration/metamorphic effects on the original columbite.

Columbite 94-24a yields an upper intercept age of 2649 ± 4 Ma based on three inversely discordant fractions (Figure 24.3). Fraction 880 plots to the left of the discordia with a $^{207}Pb/^{206}Pb$ age of 2639 ± 0.9 Ma, interpreted as a later disturbance and is therefore omitted from the age calculation.

Columbite 94-44MU5 is from a muscovite pod within the core zone of Marko's pegmatite. It is interpreted to have crystallized from volatile rich, late-stage magmatic processes. Two normally discordant fractions and three inverse discordant fractions yield an upper intercept age of 2642 ± 7.6 Ma (Figure 24.3).

Sample 99FWB74 is taken from an undeformed, quartz-rich portion of the "Big Mack" pegmatite within the southwestern subgroup of the Separation Rapids pegmatite group. Fraction 876 is concordant with a $^{207}Pb/^{206}Pb$ age of 2603 ± 2.5 Ma (2σ) (Figure 24.3).

Four fractions analyzed from a tantalite grain (SS134) within the Pakeagama Lake pegmatite have a poorly defined discordia intercept of 2649 ± 11 Ma. However, a single concordant fraction (882) provides a best age estimate for the undeformed core zone of 2645 ± 2 Ma (2σ) (Figure 24.3).

$^{40}Ar/^{39}Ar$ Geochronology

$^{40}Ar/^{39}Ar$ ages and diffusion profiles of white micas (Figures 24.4, 24.5 and 24.6) are being obtained at the Open University using high spatial resolution UV laser ablation (Kelley 1995). Initial results were presented in Smith et al. (1999) and have been supplemented with further analyses. A highly deformed tourmaline-muscovite aplite dike has a $^{40}Ar/^{39}Ar$ mica age of 2672 ± 3 Ma, and a deformed potassium feldspar-petalite dike has a similar age of 2679 ± 15 Ma.

The DIFFARG program (Wheeler 1996) uses a finite difference algorithm to simulate Ar diffusion profiles in minerals with a user-defined thermal history. Discrete re-heating events or a thermal "pulse" can be entered into the grain history, and the resulting effect on the diffusion profile is calculated. Alternatively, linear cooling histories can be modelled to simulate slow cooling of a mineral grain. A period of 10 million years was used consistently for the timing of each thermal "pulse", which enabled us to evaluate the pulse temperature that was most likely to have caused the measured diffusion profile. In each case, several thermal histories were modelled using consistent dimensions for each grain. We present the theoretical model that best matches the measured diffusion profile, as well as an example of a grain history that obviously deviates from the observed profile.

DISCUSSION

U-Pb columbite ages within the eastern subgroup of the Separation Rapids pegmatite group confirm geochemical links with the nearby Separation Rapids pluton. Sample 94-24a, a topaz-bearing, beryl-type pegmatite, has a U-Pb columbite age of 2649 ± 4 Ma. Marko's pegmatite (sample 94-44MU5), a complex-type, petalite-subtype pegmatite, has a columbite age of 2642 ± 8 Ma. These are interpreted as crystallization ages and are within error of the nearby 2646 ± 2 Ma Separation Rapids pluton (Larbi et al. 1999). This suggests that the Separation Rapids pluton and undeformed pegmatites of the eastern subgroup had a synchronous emplacement, thereby confirming genetic links described by Pan and Breaks (1997). Furthermore, fluorine, by its significant presence in the 2649 ± 4 Ma pegmatite 94-24 represents

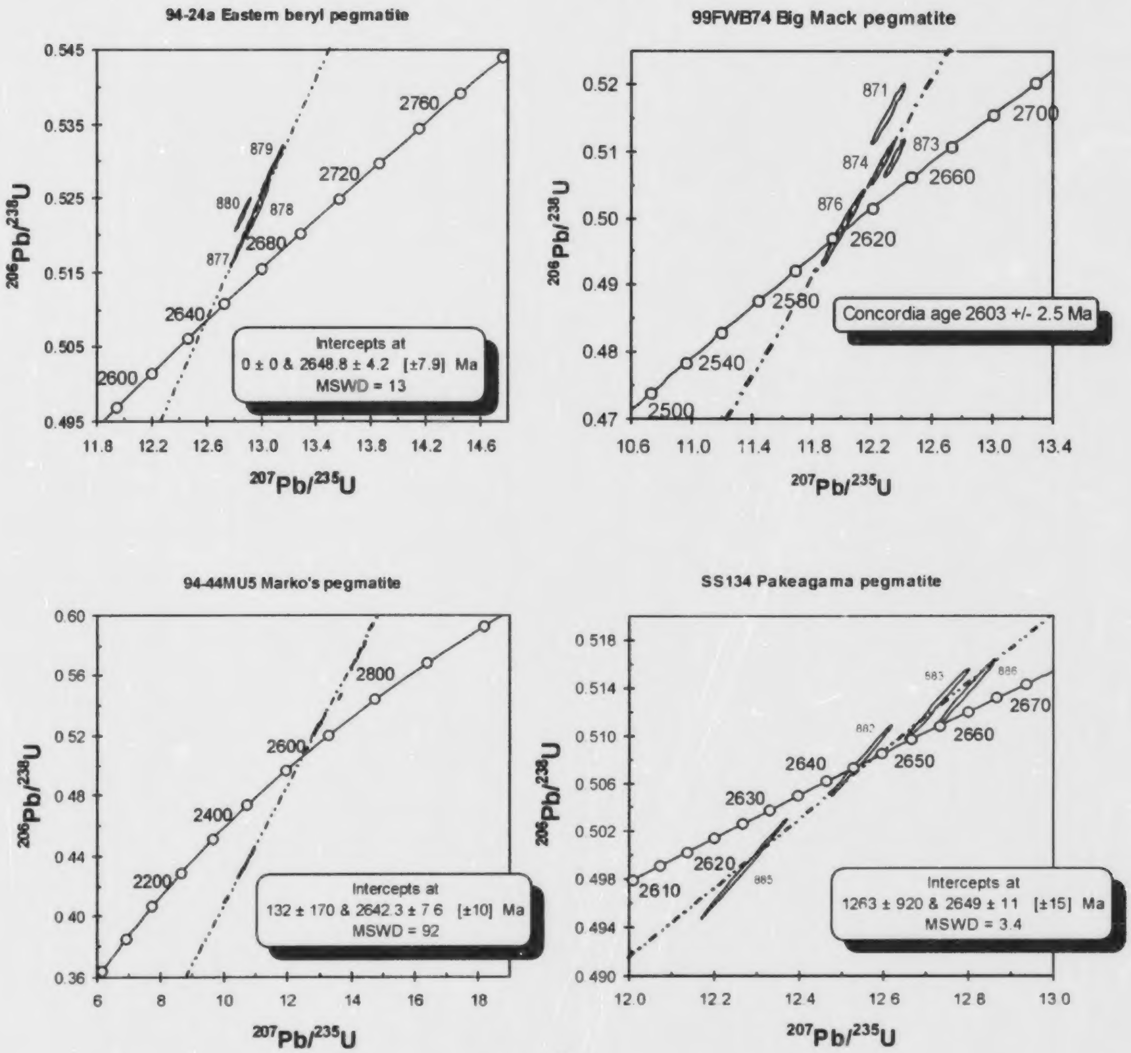

Figure 24.3. Concordia plots for columbite from the Separation Rapids pegmatites (94-24a, 94-44MU5 and 99FWB74) and the Pakeagama Lake pegmatite (SS134). All intercept ages were regressed using Isoplot/Ex v.2.22 (Ludwig 2000). Error ellipses are shown at the 2σ level. Errors including decay constant uncertainties are shown within brackets.

an important volatile component in the genetic history of the Separation Rapids pluton and adjacent rare-element pegmatites of the eastern subgroup.

However, U-Pb analyses of columbite from the southwestern subgroup are more difficult to interpret. Sample 99FWB74 is from the "Big Mack" pegmatite, a complex-type, petalite-subtype pegmatite that is variably deformed with a maximum width of 30 m and an exposed length of 200 m. Columbite from this sample has a U-Pb age of 2603 ± 2.5 Ma. Based on the compositional trend of columbite 99FWB74 (Figure 24.2), and its occurrence within a late-stage, undeformed, petalite-quartz patch of the otherwise highly deformed Big Mack pegmatite, it is unreasonable to assume that 2603 ± 2.5 Ma is the crystallization age of the main mass of the dike. Preliminary data interpretation indicates that the initial "common lead" ratios may be anomalous, perhaps due to incorporation of U, Th or Pb from inclusions, or that the initial Pb ratios were disturbed by a post-magmatic fluid influx. We are therefore continuing the investigation of this columbite to determine which of these scenarios is more probable.

^{40}Ar/^{39}Ar analyses of white micas from deformed dikes of the Pakeagama Lake pegmatites give ages of 2672 ± 3 Ma and 2679 ± 15 Ma. A single concordant fraction from amblygonite-quartz-lepidolite veins, which postdate the undeformed quartz-spodumene core zone, gives a U-Pb columbite best age estimate of 2645 ± 2 Ma. This is strikingly similar to the crystallization age of the undeformed dikes of the Separation Rapids pegmatite group and suggests that rare-element mineralization processes were synchronous across much of the northwestern Superior Province. Our data also suggest that dating of deformed and undeformed pegmatites that are located proximal to tectonic boundaries enables constraints to be placed on the final events of craton assembly in the Superior Province. It is evident that final collision related deformation along the Bear Head fault zone occurred during the period 2672 to 2645 Ma.

Diffusion profiles measured within micas indicate that ^{40}Ar/^{39}Ar systematics have been affected by two Proterozoic events, a 2.4 Ga thermal resetting and an 1850 Ma partial disturbance of the Ar-Ar system. The 2.4 Ga thermal resetting had the most prominent effect on the Separation Rapids pegmatites; ^{40}Ar/^{39}Ar ages were completely reset from the crystallization age of 2649 ± 4 Ma. Theoretical modelling of diffusion profiles from the Severn River pegmatite indicates that the re-heating reached a temperature of 450°C for at least 10 million years. Re-heating could conceivably have resulted from major basaltic underplating of the lithosphere associated with the emplacement of the Matachewan–Hearst dike swarm at 2.45 Ga (Heaman 1997). Mafic magmatism was centred on the southern Superior Province but may have had a much larger extent than the presently exposed dike swarm. Indeed, Heaman (1997) suggested that the Matachewan magmatism would have caused thermal metamorphism and heating at the base of the crust and that magmatic activity may have lasted for 30 million years with a progressive westward younging of magmatism.

Partial disturbance of the ^{40}Ar/^{39}Ar systematics at 1850 Ma is indicated by the diffusion profiles from the pegmatite suites analyzed. Theoretical modelling of these measured diffusion profiles suggests that the temperature reached during this event was between 375 and 400°C. Corfu and Ayres (1984) reported similar zircon lower intercept ages from batholiths of the North Caribou terrane. It was suggested that compressive stresses within the Superior Province, caused by the Trans-Hudson orogeny along its margins, reactivated major fault zones and resulted in partial disturbance of U-Pb systematics. Fault reactivation and shear-heating seems a plausible explanation for partial disturbance of ^{40}Ar/^{39}Ar systematics in micas from rare-element pegmatites located along tectonic boundaries.

Hanes and Archibald (1998) also found similar apparent ages (~2.4 Ga from biotite and 1.7 to 1.9 Ga from potassium feldspar step-heating experiments) from a transect across the English River Subprovince, and related this to uplift and fault reactivation.

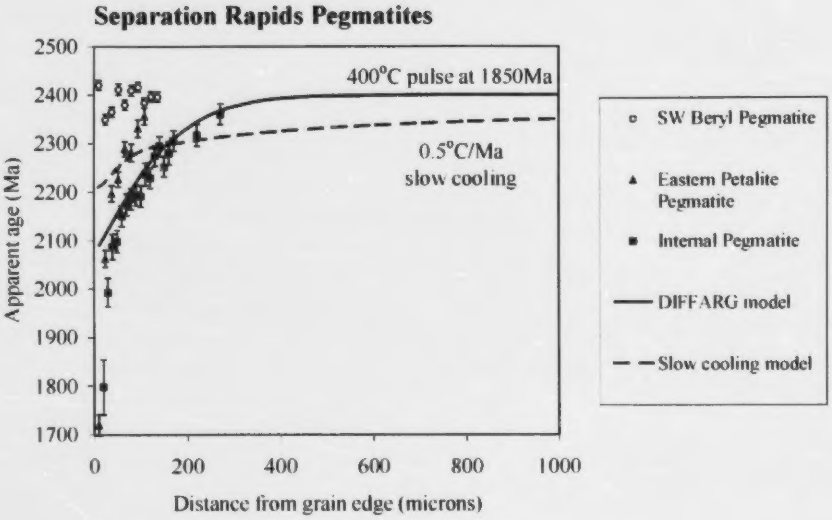

Figure 24.4. Ar diffusion profiles from the Separation Rapids pegmatites; all $^{40}Ar/^{39}Ar$ ages have been reset to 2.4 Ga. Theoretical modelling of Ar diffusion profiles clearly shows that a second partial disturbance of $^{40}Ar/^{39}Ar$ systematics has occurred at 1850 Ma. Younger apparent ages measured at the edge of the grains are not easily accounted for; these may represent a third heating event of unknown age.

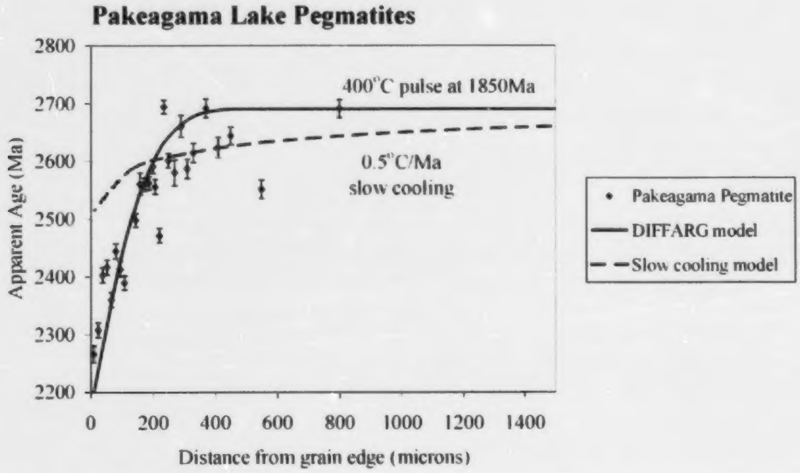

Figure 24.5. Ar diffusion profile from the Pakeagama Lake pegmatite. Slow cooling models cannot account for the measured diffusion profile. Instead, a short-lived rise in temperature at 1850 Ma is the most probably scenario, as shown by the theoretical model.

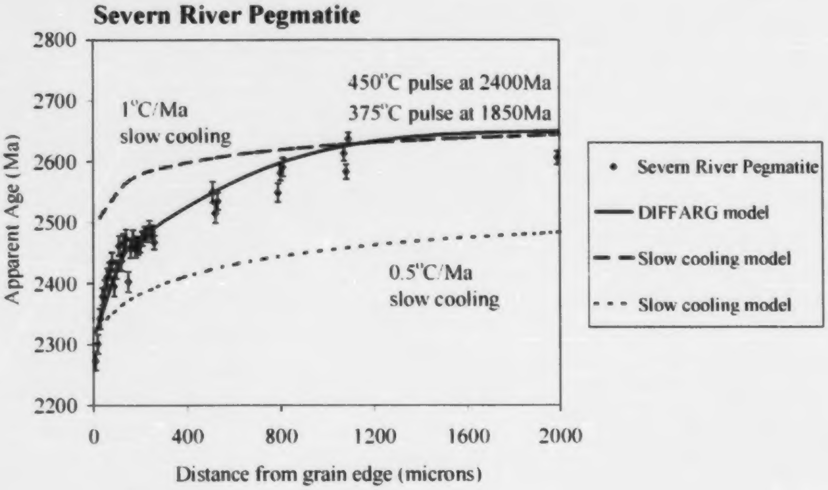

Figure 24.6. Ar diffusion profile from the Severn River pegmatite, also located along the Bear Head fault zone, close to the Pakeagama Lake pegmatites. The measured diffusion profile can be matched almost exactly by theoretical modelling of two reheating events at 2400 Ma and 1850 Ma. Even at very slow rates (0.5°C/Ma), slow cooling models do not match the measured diffusion profile and are therefore discounted as a reason for the variation in $^{40}Ar/^{39}Ar$ apparent ages.

High spatial resolution UV laser ablation and theoretical modelling suggest that slow cooling cannot account for the measured $^{40}Ar/^{39}Ar$ diffusion profiles. Slow cooling on timescales >200 Ma is therefore rejected as a process for producing the younger apparent ages measured in these rare-element pegmatite micas.

CONCLUSIONS

Rare-element pegmatites provide excellent markers for the late syn- to post-orogenic processes and deformation of Archean terrains such as the Superior Province. Differences in the crystallization age of rare-element pegmatites that are spatially associated, as well as being chemically and mineralogically similar, can be resolved using combined U-Pb columbite-tantalite and $^{40}Ar/^{39}Ar$ mica geochronology. $^{40}Ar/^{39}Ar$ diffusion profiles obtained by high spatial resolution UV laser ablation constrains the timing and prominence of later re-heating events from disturbances to the isotopic system, although care must be taken when interpreting $^{40}Ar/^{39}Ar$ apparent ages.

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25. Project Unit 00-001. Structural Investigation of Mesothermal Gold Mineralization in the Beardmore–Geraldton Terrane

J.C. DeWolfe[1], B. Lafrance[1], and G.M. Stott[2]

[1]Department of Earth Science, Laurentian University
[2]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Beardmore–Geraldton Terrane (BGT) (Figure 25.1) is located in the Archean Superior Province of Ontario, forming a transitional zone between the granite-greenstone Wabigoon Subprovince to the north and metasedimentary Quetico Subprovince to the south (Williams and Stott 1991). The BGT consists of three distinct east-trending, steeply dipping metasedimentary belts, namely, the Northern, Central and Southern Belts (Mackasey 1975, 1976). The metasedimentary belts are separated by metavolcanic belts. Regional metamorphic grade throughout the study area is lower greenschist facies, and is characterized by abundant pervasive chlorite and epidote. Younging indicators in both metasedimentary rocks (i.e., graded-bedding) and metavolcanic rocks (i.e., pillow basalt cusps) suggest that the belts generally young to the north. Regional brittle-ductile deformation zones, such as the Paint Lake Deformation Zone (Reilly 1987), commonly mark the boundaries between the metavolcanic and metasedimentary belts. These regional shear zones host mesothermal gold occurrences, which are the focus of this study.

The BGT is a well-known past-producing gold belt in Ontario. Since the early 1900s, the BGT has produced more than 250 000 ounces of gold from 18 mines. Although there are no current producers in the BGT, active exploration for mesothermal gold ranges from grassroots prospecting by local prospectors to advanced exploration projects such as the Ontex Resources Limited Brookbank project (Figure 25.1).

The study area for this project extends across Irwin and Walters Townships, where it covers a 3 km (north-south) by 13 km (east-west) section of the Northern and Central Metasedimentary Belts, and their bounding metavolcanic belts. This study area was selected because it includes a section of the Paint Lake Deformation Zone (Figure 25.1), along with several mesothermal gold occurrences associated with splays of the deformation zone. The main objective of the study is to produce a new regional structural map that will be used in the interpretation of the structural and tectonic history of the belt. A second objective of the study is to constrain regional and deposit scale controls on gold mineralization in the belt. Thus, regional mapping of faults and shear zones in the map area will be complemented by detailed outcrop mapping of gold occurrences and deposits. This report summarizes field observations in Irwin and Walters Townships during the first of a two-year study.

ROCK UNITS OF THE STUDY AREA

Metasedimentary Units

NORTHERN METASEDIMENTARY BELT

The Northern Metasedimentary Belt (Figure 25.1) comprises a 0.1 km wide polymictic conglomerate, which is nearly continuously exposed for several kilometres along the south shore of Paint Lake. The conglomerate is steeply dipping and east trending. The conglomerate lies along the Paint Lake Deformation Zone, and is strongly deformed by the east-trending schistosity of the deformation zone. Clasts range in size from pebbles to cobbles. The majority of clasts are granitic, but clasts of diorite or gabbro, felsic to mafic volcanic rocks, and sedimentary rock, such as a thinly laminated red chert are also present. The granitic clasts are well rounded, appear to be relatively undeformed, and are oriented with their long axis sub-parallel to the regional east-trending schistosity. Many of the granitic clasts have asymmetric pressure shadows indicating dextral shear, and in many cases, the clasts were back-rotated during the shear (Figure 25.2A). Many of the granitic clasts also display quartz ladder veins, which are perpendicular to the schistosity. In contrast to the granitic clasts, volcanic and sedimentary clasts in the conglomerate are highly deformed, and often stretched out to thin lenses.

The matrix of the conglomerate consists of fine- to medium-grained sandstone, with few siltstone horizons. Matrix to clast ratios vary considerably, ranging from closely packed clasts with little matrix material, to matrix-supported beds with 60% or more matrix material. In zones of intense shearing, the matrix is schistose and chloritic, and matrix to clast ratio is difficult to estimate because of similarities in

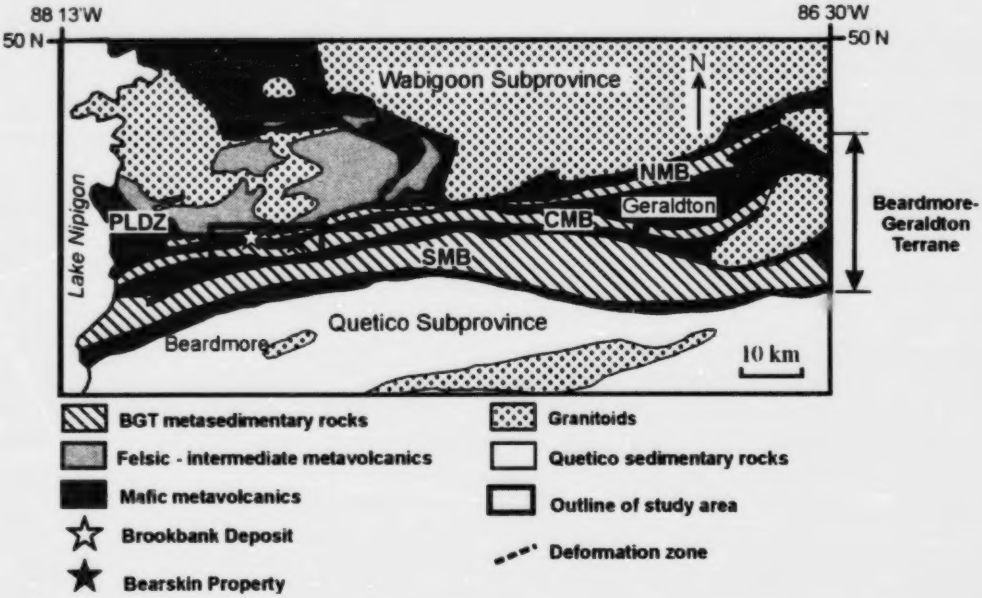


Figure 25.1. Simplified Geology of the Beardmore–Geraldton Terrane, *after* Williams (1987). NMB = Northern Metasedimentary Belt, CMB = Central Metasedimentary Belt, SMB = Southern Metasedimentary Belt, PLDZ = Paint Lake Deformation Zone.

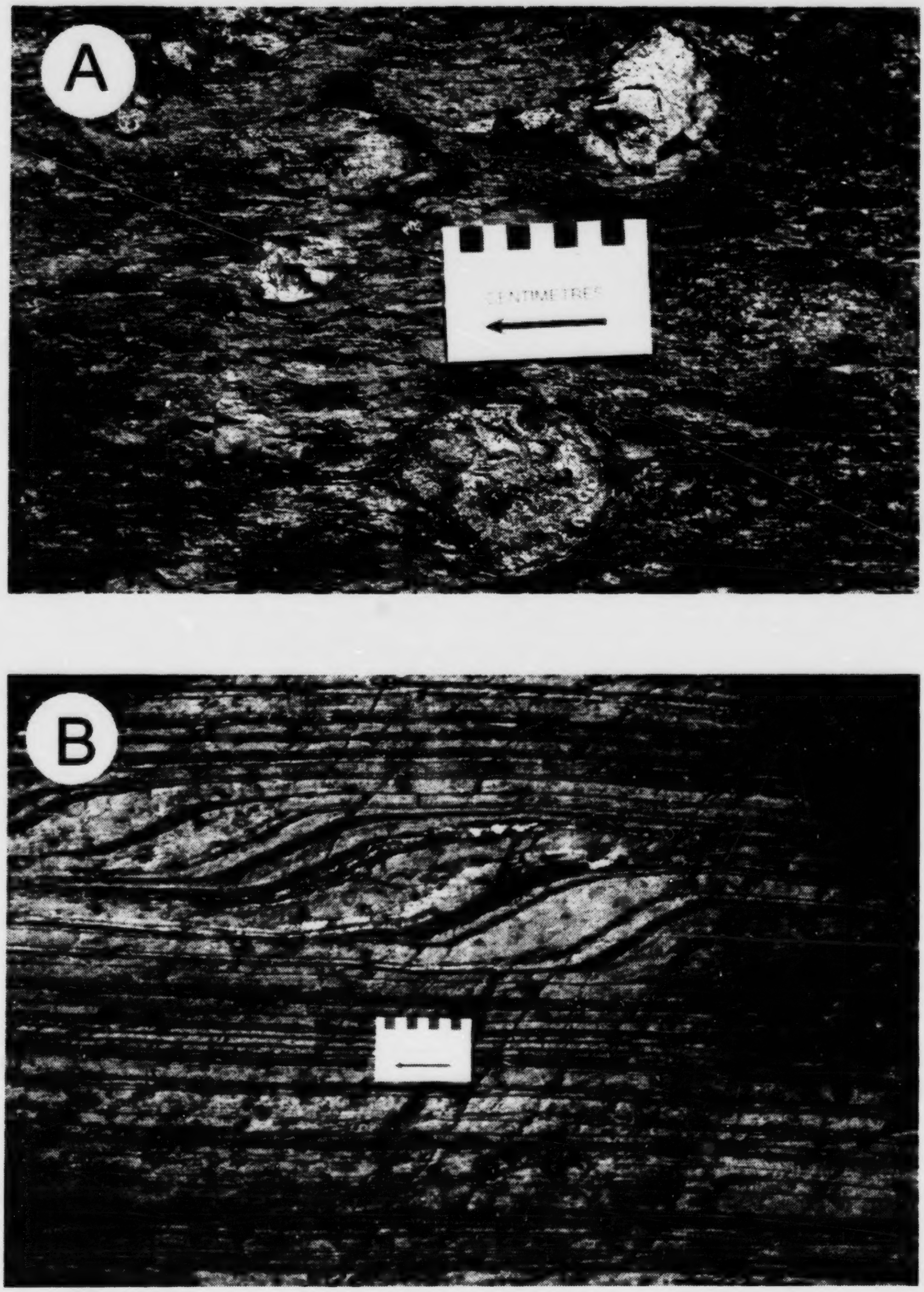


Figure 25.2. Photographs of tectonic structures present in the BGT. (A) Dextral shearing indicated by delta structures formed around back-rotated granitic clasts in polymictic conglomerate. Card for scale, facing south. (B) Open F1 S-folds in banded iron formation and wacke. Note S3 cleavage cutting across layering. Card for scale, facing north.

appearance between some of the volcanic clasts and the matrix material. With the exception of possible graded bedding in a few locations, no primary sedimentary structure is present in the conglomerate.

CENTRAL METASEDIMENTARY BELT

The Central Metasedimentary Belt (Figure 25.1) in the map area consists of a 0.75 km wide section of sporadic to more continuous outcrops of argillite, sandstone, siltstone and minor polymictic conglomerate. The sandstones are thinly to thickly bedded (5 to 30 cm thick beds) and are interlayered with 5 to 15 cm thick siltstone beds. Graded beds in the sandstones are younging to the north. The sandstones are composed mainly of mafic lithic clasts, with few massive feldspar-rich horizons. The feldspathic sandstone is medium to coarse grained and consists principally of pink feldspar and minor quartz. Thin layers in the sandstones are conglomeratic with a clast composition similar to that of the polymictic conglomerate of the Northern Metasedimentary Belt.

Metavolcanic Units

MAFIC METAVOLCANIC ROCKS

The mafic metavolcanic rocks (Figure 25.1) form a 2 km thick, east-trending belt, which is bounded to the north by the Northern Metasedimentary Belt, and to the south by the Central Metasedimentary Belt. This belt is referred to as the Northern Metavolcanic Belt by Devaney and Williams (1989). The basalts are fine to medium grained, dark greenish-black, massive flows that are typically tens of metres thick, with few isolated occurrences of pillow basalts. Minor flow breccias composed of angular fine-grained basalt fragments (2 to 10 cm in size) are associated with the massive flows. The flow breccia occurs as narrow discontinuous and irregular lenses in the massive flows.

INTERMEDIATE-FELSIC METAVOLCANIC ROCKS

The northern limit of the study area is marked by a 0.2 km thick unit of intermediate to felsic volcanic rocks (Figure 25.1). This unit is a small section of the thick Elmhirst–Rickaby intermediate to felsic volcanic pile (Stott 1984). The intermediate to felsic volcanic rocks range from massive flows to layered tuff. The massive flows are light grey-green in colour to locally purplish-red. Apparent compositional banding in the tuff is defined by alternating pink and green layers.

Intrusive Igneous Units

MAFIC INTRUSIONS

Medium-grained gabbros are associated with the mafic metavolcanic rocks. They are medium grained, dark green to black, and composed of feldspar and amphibole phenocrysts in a matrix of mafic minerals. These gabbros are interpreted as coarse centres of flows (Mackasey 1975, 1976), because of the lack of exposed intrusive contacts.

INTERMEDIATE INTRUSIONS

North of Paint Lake, dioritic intrusions cut across intermediate metavolcanic rocks. The diorite is medium to coarse grained, and consists of equigranular feldspar and amphibole. The intrusions form roughly east-trending ridges, up to several hundred metres in length, and are weakly foliated. A quartz-feldspar porphyry intruded massive basalts in the Bearskin property (Figure 25.1). The porphyry forms a cluster of small intrusions composed of rounded, quartz and feldspar phenocrysts 0.5 to 1.0 cm in diameter in a fine-grained intermediate matrix. Contacts between the porphyry and basalt are welded, with no visible chilled margins present. The welded contacts, along with the lack of hydrothermal alteration of the host basalt by the porphyries, suggest intrusion while the basalt was still cooling.

FELSIC INTRUSIONS

A distinct suite of quartz-feldspar porphyry intrusions, located in the Bearskin Property (Figure 25.1) contains minor pyrite and chalcopyrite mineralization. This second porphyritic suite differs from the intermediate quartz-feldspar porphyry in that it consists almost entirely of quartz and feldspar phenocrysts in a fine-grained quartz-feldspar matrix. It is commonly pegmatitic with quartz veins cutting through large feldspar phenocrysts.

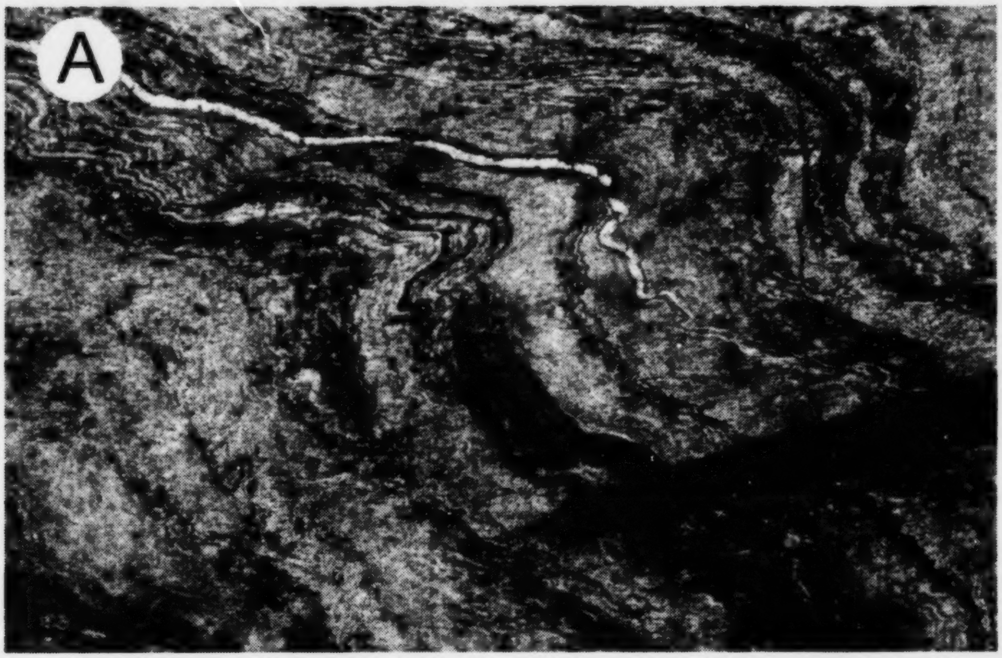
STRUCTURE

A number of tectonic structures are present throughout the field area. The majority of these structures are related to the east-trending Paint Lake Deformation Zone (Figure 25.1). Planar and linear structural features and kinematic indicators within the study area record 4 successive periods of deformation (D_1 to D_4).

D_1 is represented by mesoscale S-folds (F_1) (Figure 25.2B). F_1 folds are rarely preserved, except in banded iron formation of the Southern Metasedimentary Belt, and in S-folded quartz veins scattered throughout the other belts. F_1 folds are tight to open folds with thickened short limbs and attenuated long limbs as a result of strong compression perpendicular to the fold axial planes.

D_2 is a period of dextral shearing, represented by a regional east-trending, steeply dipping schistosity (S_2). The S_2 schistosity is subparallel to primary layering throughout the study area, but is slightly counterclockwise to bedding in more competent rock units. S_2 varies from weak to intense throughout the study area, especially in the basalts, where massive sections of weakly foliated basalts are cut by 2 to 5 m thick zones of intense foliation. Associated with this foliation is a shallowly plunging slickenside lineation (L_{2a}). When steps across L_{2a} are present, they indicate a dextral sense of movement along the deformation zone. A steeply plunging mineral lineation (L_{2b}) is also observed in a few outcrops throughout the belt. L_{2b} is defined by steeply plunging, elongate crystals of amphibole and chlorite, and is best developed outside of the zones of intense dextral shearing.

D_3 structures are spatially associated with D_2 shear zones. Southwest-plunging asymmetrical Z-folds (F_3) formed during this event (Figure 25.3A). F_3 folds have a southwest-trending, steeply dipping axial-planar cleavage (S_3) that cross-cuts earlier deformational fabrics. The orientation of the S_3 cleavage refracts from southwest-trending in more competent sandstone layers, to a slightly more west-southwest trend in the less competent shale layers.



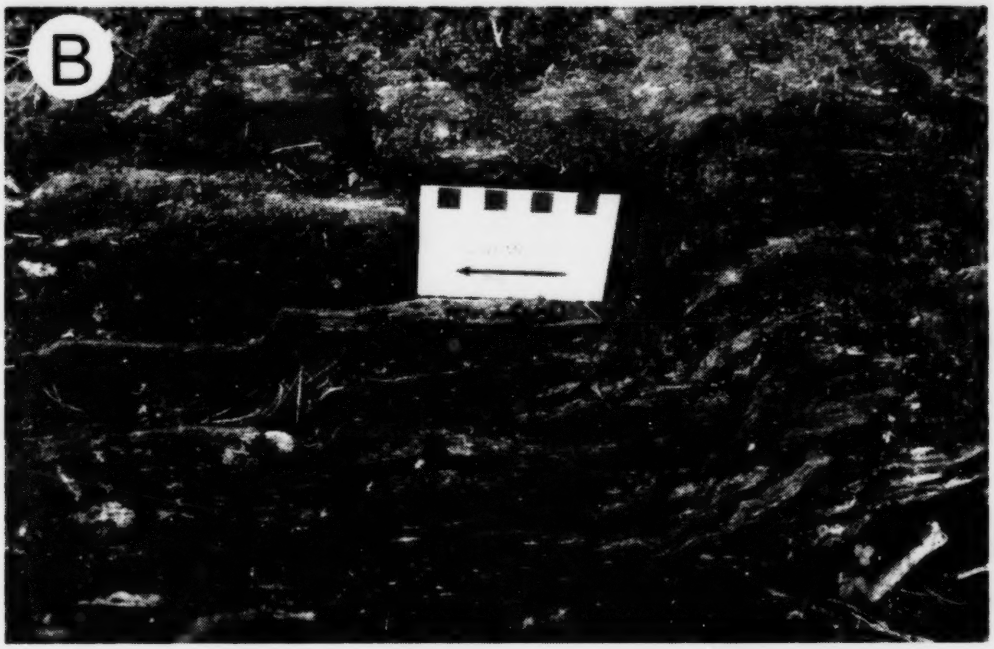


Figure 25.3. Photographs of tectonic structures present in the BGT. (A) F3 Z-folds with axial-planar S3 cleavage (parallel to pencil) and S2 foliation (parallel to layering in rock) in interlayered sandstone and siltstone. Pencil for scale, facing north. (B) F4 sinistral kink folds in intermediate volcanic rocks. Card for scale, facing north.

D_4 produced a late generation of sinistral kink folds (F_4) overprinting all previous deformational fabrics (Figure 25.3B). Fold axis for the F_4 kinks plunge steeply to the southwest. The F_4 folds are rare, but they have been observed in all lithologies throughout the study area.

The D_2, D_3, and D_4 structures are interpreted as the products of a progressive dextral shear deformation which began and ended with the development of D_2, D_3, and D_4 structures, respectively.

ECONOMIC GEOLOGY

Different types of hydrothermal alteration zones are present throughout the metavolcanic and metasedimentary belts. They consist of vein, selective pervasive, and pervasive styles of alteration. The most prevalent alteration type is a locally pervasive propylitic alteration, consisting of chlorite, epidote, and minor carbonate. In intensely sheared basalts and conglomerates, the rocks are commonly almost entirely altered to chlorite. There are zones throughout the field area where epidote becomes the dominant alteration mineral, and it occurs as both patches of pervasive alteration, and as veins or veinlets. Vein style epidote alteration often occurs as zones of closely spaced, parallel sheeted veins (particularly in basalts of the Bearskin Property).

Pervasive ankerite alteration is associated with a number of large quartz veins (typically 1.5 m thick) and shear zones. This is an intense alteration that entirely replaces host rocks within 0.5 m of the veins, decreasing outwards in intensity for several metres. Throughout the map area, shear-related pervasive ankerite alteration zones without quartz veins are commonly tens of metres thick.

Alteration zones associated with gold occurrences may record single stage or multi-stage alterations. For example, alteration zones of ankerite, chlorite, epidote, quartz flooding, and potassium feldspar were all observed in the Brookbank Zone (Figure 25.1). The alteration zones are often associated with faults, shear zones, and quartz veins, and therefore show a high degree of structural control. The Brookbank auriferous zone is owned by Ontex Resources Limited. Inferred mineral resources for the Brookbank Zone, calculated in 1990 by Placer Dome, are 1,253,594 tonnes at 9.01 grams of gold per tonne (Ontex Resources Ltd. Annual Report, 1999). A M.Sc. thesis by Kowalski (1993) shows a distinct correlation between pyrite and gold mineralization at the Brookbank Zone. Sulphide mineralization, consisting mostly of pyrite but with zones of arsenopyrite and chalcopyrite, occurs throughout the study area in quartz veins, and disseminations in the host rocks. Comparison of channel sample assays for the Brookbank Zone, provided by Ontex Resources Ltd, shows a strong correlation between elevated gold assays and the presence of both potassic and silicious hydrothermal alteration. This relationship between alteration and mineralization is also observed in diamond drill core by Ontex geologists.

CONCLUSIONS

Two key conclusions result from the study, as follows:

1. Four periods of brittle-ductile deformation: Overprinting relationships of planar and linear features record four distinct deformational events in the study area, with three of these events (D_2, D_3, and D_4) interpreted to be products of a progressive dextral shear deformation.

2. Relationship between gold mineralization and structurally controlled hydrothermal alteration: Elevated gold assays are associated with potassium and silica hydrothermal alteration centred on a number of different structural features.

Future work will include follow-up mapping of shear zones and gold occurrences in the BGT. Petrographic and scanning electron microscope (SEM) studies of microstructures will be done on samples collected from the study area. The field and lab data will be integrated with remote sensing and geophysical maps to develop a regional-scale predictive model of faulting and associated gold mineralization in the BGT.

ACKNOWLEDGMENTS

Funding for this project is provided by the OGS as part of the Laurentian University–OGS mapping masters program. Further funding is provided by NSERC and Lithoprobe Grants received by Dr. B. Lafrance. Colin Bowdidge of St. Anthony Resources, and Armen Chilian, Ray Knowles, and the staff of Ontex Resources are thanked for sharing their knowledge, as well as for providing access to their property and data. Thanks also to OGS Regional Geologists Gerry White and John Mason, along with the prospectors of the Beardmore area for their assistance during the field season.

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26. Project Unit 99-011. Geochemistry of Hydrothermal Alteration and Its Relation to Base-Metal Mineralization in the Marshall Lake Area, Northern Margin of the Onaman–Tashota Greenstone Belt

K.H. Straub[1]

[1]Department of Earth Sciences, Laurentian University

INTRODUCTION

This study constitutes a portion of an MSc mapping thesis, part of a collaborative agreement between the Ontario Geological Survey and Laurentian University, under the supervision of H.L. Gibson (Laurentian University) and G.M. Stott (Ontario Geological Survey). The objective of the thesis is to provide an updated detailed geological map of both the bedrock geology and the alteration and coincident mineralization in the Marshall Lake area (*see* Stott, Straub and Phillips 2000). This report is a brief summary of the relationships between the alteration and the surrounding host rocks, and a calculation of mass gains and losses associated with hydrothermal alteration. For a full and expanded description of the geology in the Marshall Lake region see Stott and Straub (1999) and Straub (1999). This detailed study is part of a 5-year geological survey of the Onaman–Tashota greenstone belt being undertaken by G.M. Stott.

The Marshall Lake Cu-Zn-Ag prospect occurs as a series of 5 lenses of stratabound, stringer and disseminated sulphide minerals, hosted in hydrothermally altered intermediate to felsic volcanic rocks. These sulphide occurrences have been the subject of numerous exploration ventures for over 50 years following the initial discovery by Teck-Hughes Gold Mines Ltd. (*see* Amukun 1989 for a historical overview). Located approximately 120 km northwest of Geraldton (Figure 26.1), the Marshall prospect occurs within the east-trending Marshall assemblage of felsic to intermediate volcanic rocks. This assemblage includes volcaniclastic and effusive units, porphyritic and non-porphyritic felsic intrusions, and local mafic dikes.

Several distinct alteration types exist in the area, they principally include 1) biotite-cordierite, 2) sericite-aluminosilicate, 3) silica-sericite, and 4) garnet-amphibole. Alteration types 1, 2, and 3 are related to the base-metal mineralization. The paragenesis and the distribution of these alteration types provide excellent vectors to sulphide accumulations within the mineralized horizon. Alterations such as silicification and sericitization exemplify this. The garnet-amphibole alteration observed across the region is the typical broad background effect of synvolcanic hydrothermal iron-magnesium enrichment and is not useful for locating areas of base-metal mineralization.

GEOLOGY OF THE MAP AREA

The volcanic bedding in the area strikes northwards, dipping moderately and facing eastward. The rocks have undergone two phases of penetrative deformation. (Figure 26.2). Folding in this area results

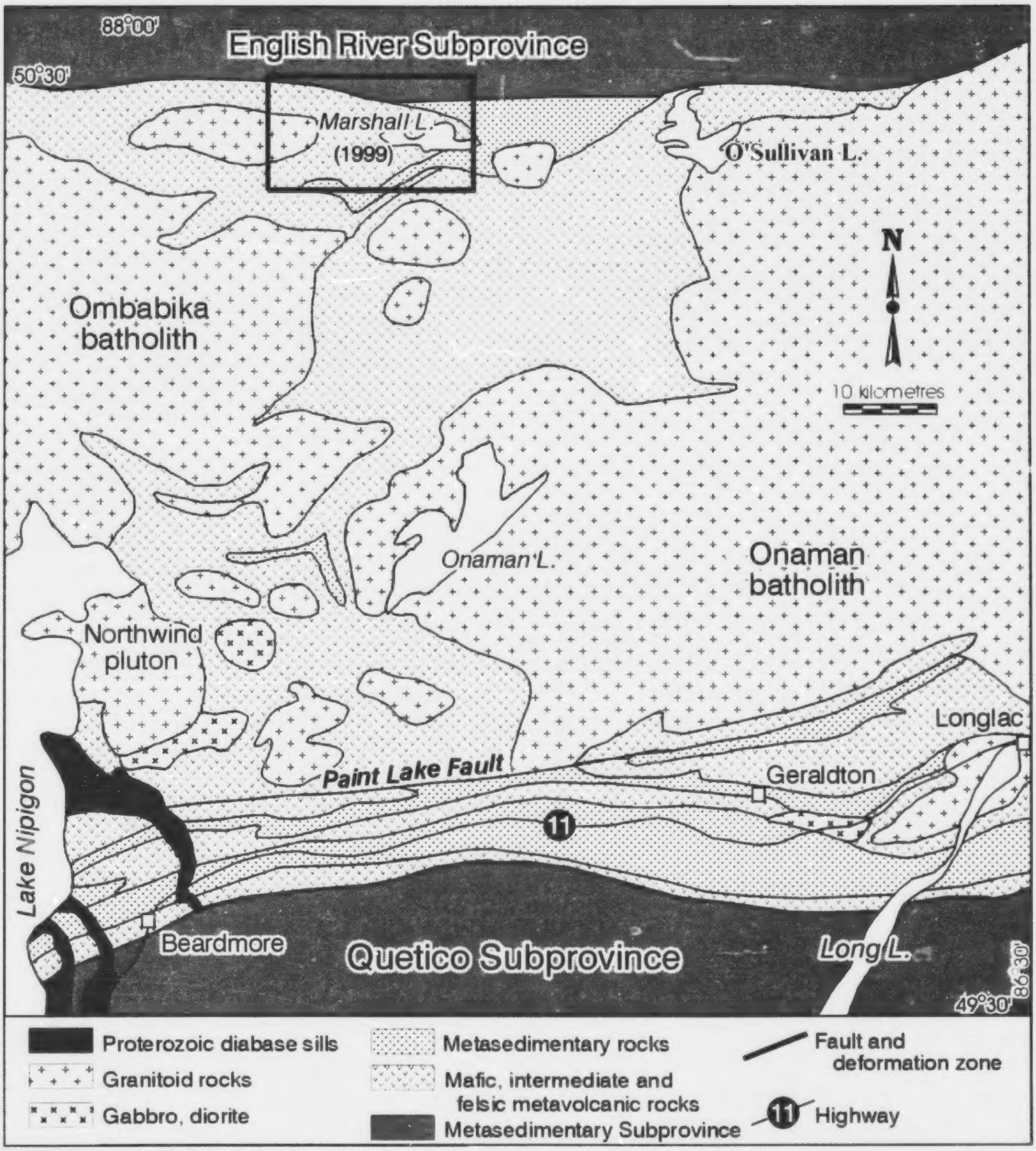
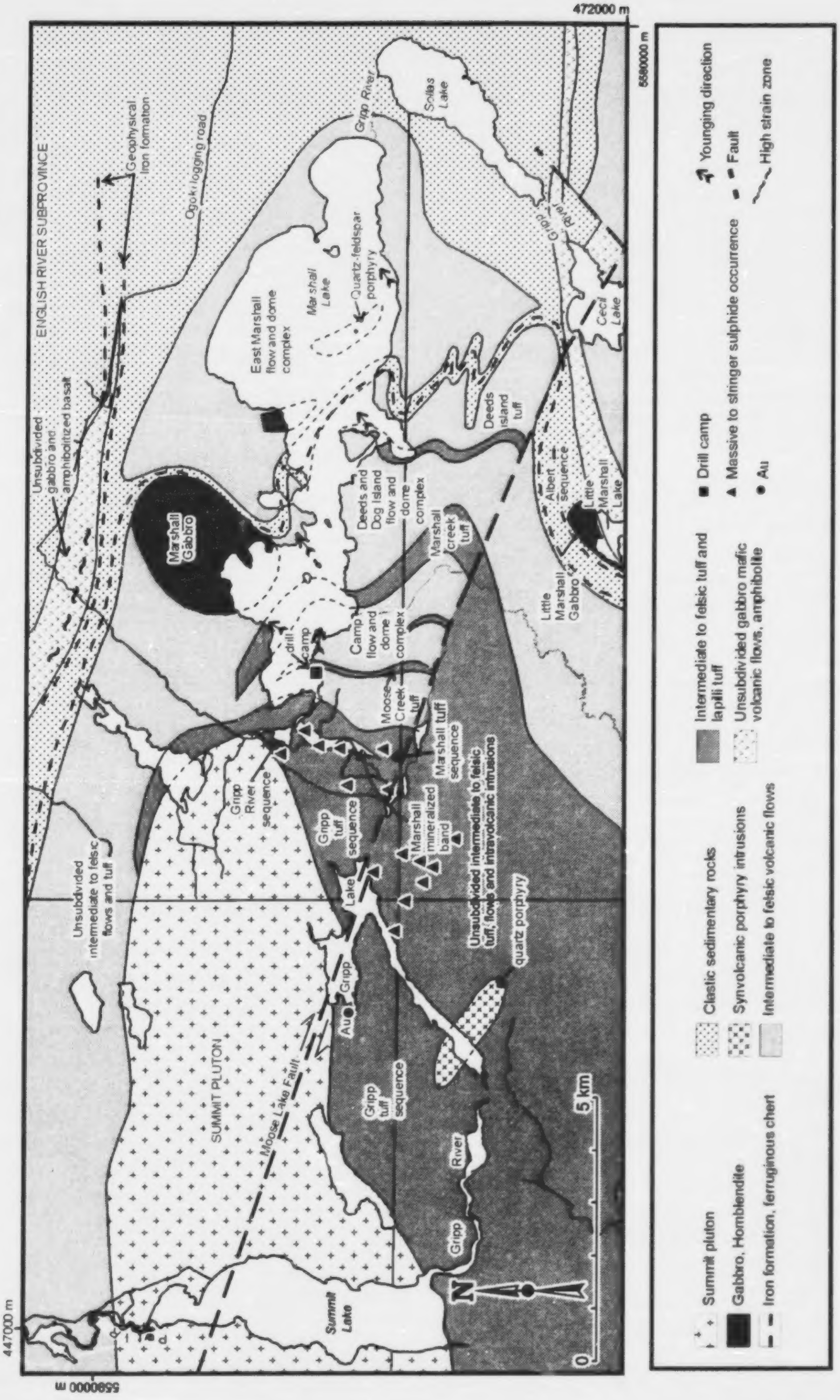


Figure 26.1. Location of the Marshall Lake area on the northern margin of the Onaman–Tashota greenstone belt, eastern Wabigoon Subprovince.


472000 m
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ENGLISH RIVER SUBPROVINCE
Geophysical iron formation
Ogoki logging road
Unsubdivided gabbro and amphibolitized basalt
Unsubdivided intermediate to felsic flows and tuff
SUMMIT PLUTON
Moose Lake Fault
Summit Lake
Gripp River
Gripp tuff sequence
Gripp Lake
Au
quartz porphyry
Unsubdivided intermediate to felsic tuff, flows and intravolcanic intrusions
Marshall mineralized band
Gripp tuff sequence
Gripp River sequence
Marshall tuff sequence
Moose Creek tuff
drill camp
Camp flow and dome complex
Marshall Gabbro
Marshall Creek tuff
Deeds and Dog Island flow and dome complex
Little Marshall Gabbro
East Marshall flow and dome complex
Deeds Island tuff
Albert sequence
Little Marshall Lake
Marshall Lake
Quartz-feldspar porphyry
Cecil Lake
Gripp River
Solias Lake
N
0
5 km
Summit pluton
Gabbro, Hornblendite
Iron formation, ferruginous chert
Clastic sedimentary rocks
Synvolcanic porphyry intrusions
Intermediate to felsic volcanic flows
Intermediate to felsic tuff and lapilli tuff
Unsubdivided gabbro mafic volcanic flows, amphibolite
Drill camp
Massive to stringer sulphide occurrence
Au
Younging direction
Fault
High strain zone

Figure 26.2. Regional geology of the Marshall Lake area (*after* Stott, Straub and Phillips 2000).

from southeast-directed compression related to a regional transpressive event. The structure in the immediate map area reflects the overall structural pattern of the Marshall Lake region (*see* Stott, Straub and Phillips 2000).

Calc-alkaline volcaniclastic dacite dominates the Marshall Lake area with subordinate massive dacite domes and breccia, and dacitic intrusions. Chemically these lithologies are homogeneous (Figures 26.3a and 26.3b). The volcaniclastic rocks have been termed the "Marshall tuff sequence" within which lies the Marshall mineralized band (Figures 26.4 and 26.5), a silicified tuffaceous zone that hosts several base metal occurrences. The dominant foliated to laminated volcaniclastic rocks contain intervening zones of more massive dacite. The grain size of the volcaniclastic units varies from fine to coarse ash with local zones of crystal and lapilli rich material. *The terms "tuff" and "lapilli tuff" are used in this report only as a guide to grain size without implying environments or mechanisms of formation.*

The lowermost sequence of the volcaniclastic rocks in the map area consists principally of massive to well-foliated, very thickly bedded, quartz porphyritic to aphanitic tuff that is locally graded. Units containing lapilli fragments and preserved bedding were traced locally in the field. These rocks are intruded by massive, aphanitic to weakly porphyritic sub-volcanic sills and possible cryptodomes shown schematically in Figure 26.4. Rocks in this sequence vary from relatively unaltered to locally moderately altered containing biotite-cordierite, sericite-andalusite, or silica-sericite. In zones of increased alteration, these rocks often contain up to 5% disseminated and fracture-filled sulphide, and rare zones of semi-massive to massive mineralization (Figure 26.6a).

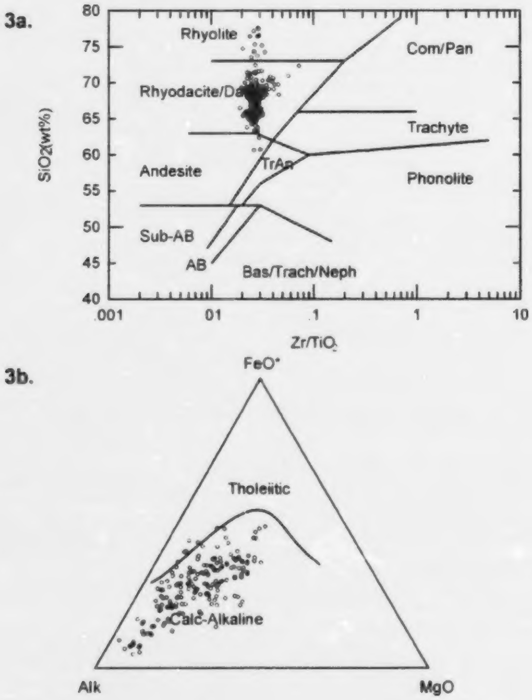

Figure 26.3. a) SiO_2 versus Zr/TiO_2 geochemical plot of least-altered Marshall Lake volcanic rocks showing predominance of dacitic to rhyodacitic compositions. **b)** AFM geochemical plot showing calc-alkaline magmatic affinity of Marshall Lake dacitic volcanic rocks.

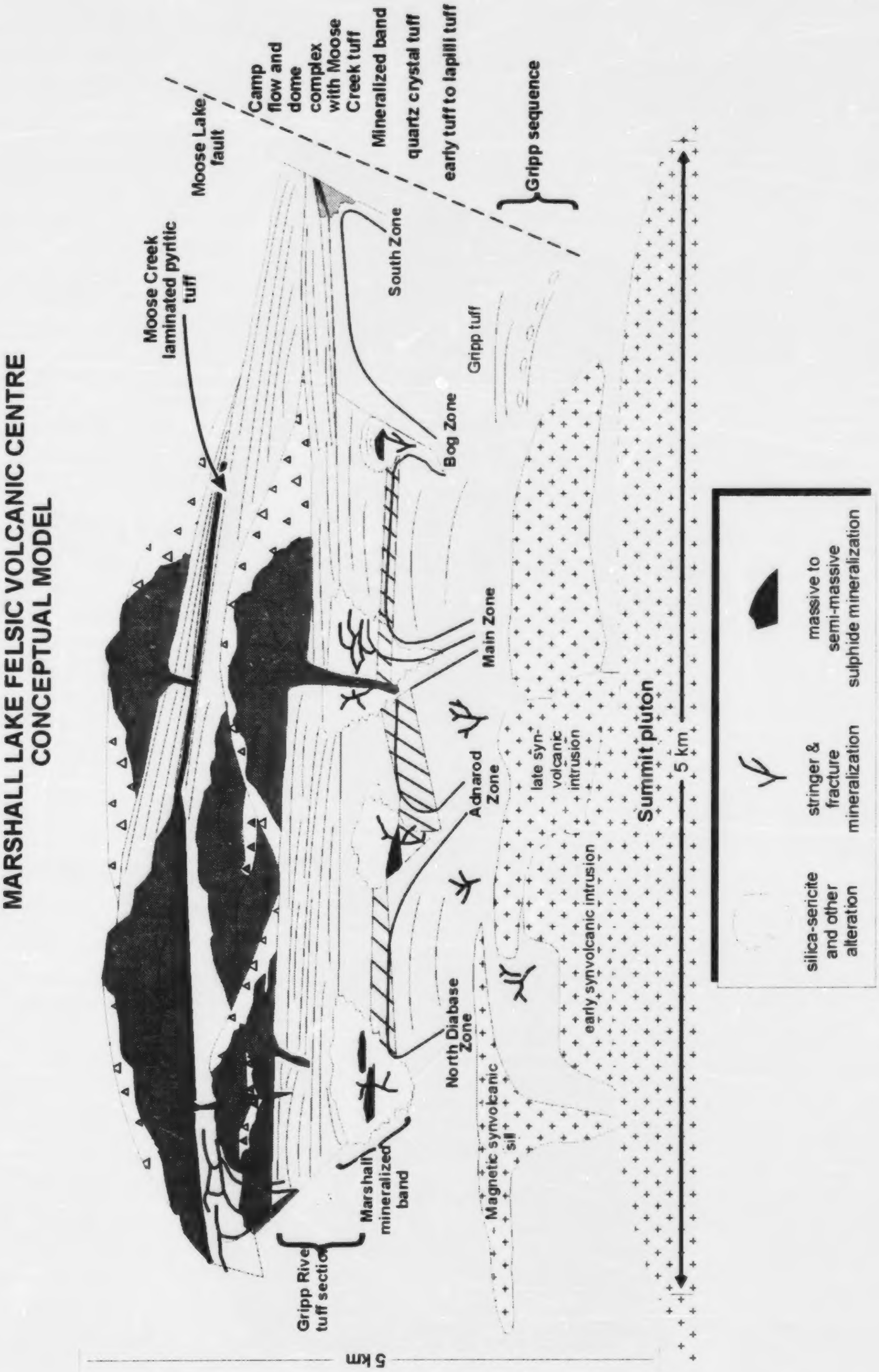
MARSHALL LAKE FELSIC VOLCANIC CENTRE
CONCEPTUAL MODEL
Moose Creek laminated pyritic tuff
Moose Lake fault
Camp flow and dome complex with Moose Creek tuff
Mineralized band
quartz crystal tuff
early tuff to lapilli tuff
Gripp sequence
South Zone
Gripp tuff
Bog Zone
Main Zone
Adnarod Zone
late syn-volcanic intrusion
early synvolcanic intrusion
Summit pluton
5 km
North Diabase Zone
Magnetic synvolcanic sil
Marshall mineralized band
Gripp Rive tuff sectio
5 km
silica-sericite and other alteration
stringer & fracture mineralization
massive to semi-massive sulphide mineralization

Figure 26.4. Schematic model of the Marshall Lake felsic volcanic centre showing the stratigraphic position of the mineralized zones.

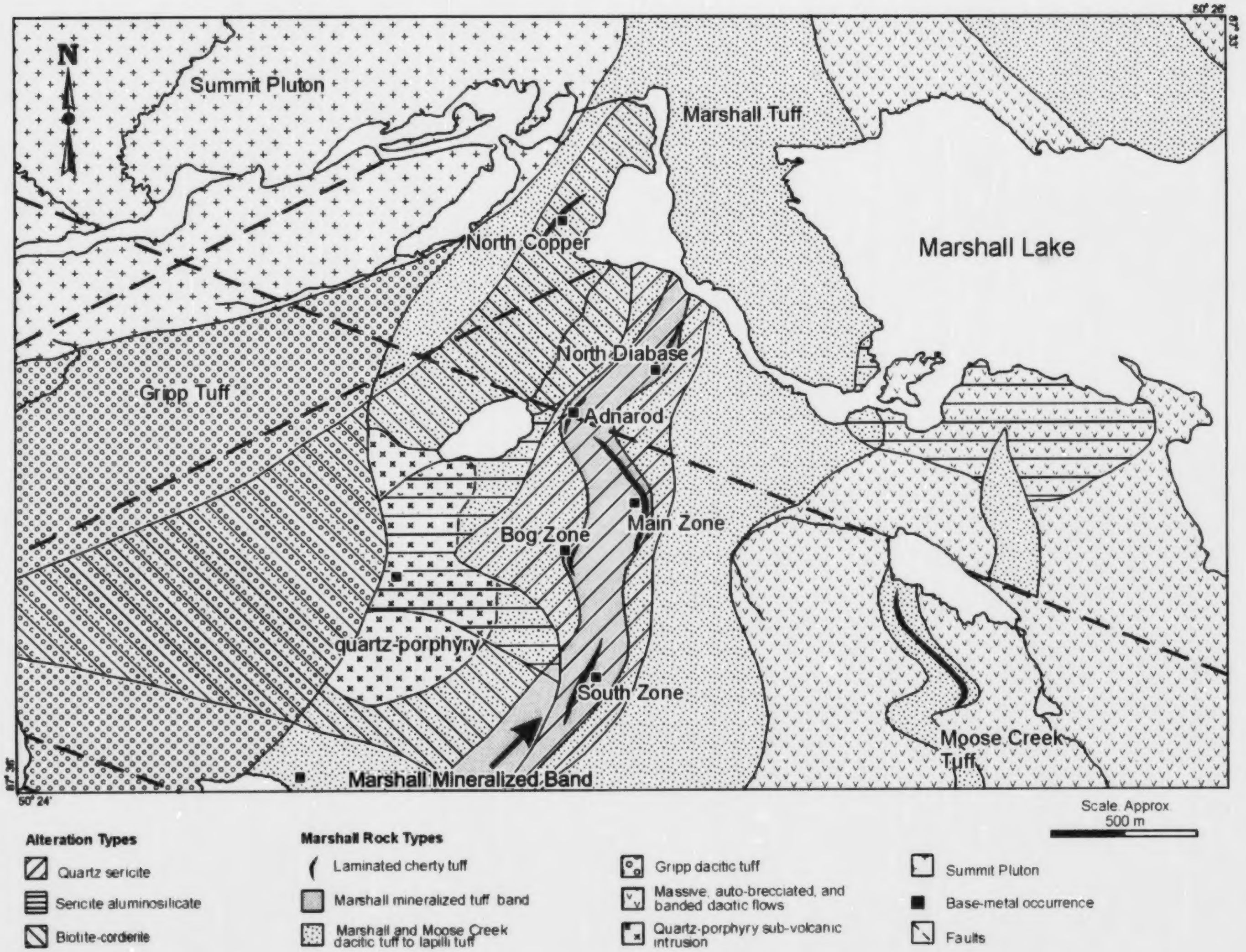

Figure 26.5. Distribution of the principal types of alteration associated with base-metal mineralization in the Marshall Lake area.

Thick sections on the order of metres to tens of metres of massive to weakly foliated quartz and/or biotite porphyry intrusions stratigraphically underlie the mineralized zones. These rocks are similar, both chemically and physically, to the volcaniclastic rocks and range from unaltered to moderately altered. Their grain size can vary from very fine to medium grained. These massive intrusions have been subdivided based on mineralogical characteristics. Several distinct quartz- and/or biotite-bearing intrusions are present in the underlying sequence to the base metal mineralization. All three of the volcanogenic massive sulphide style alterations mentioned below may locally affect some of these units. Only one unaltered phase of an intrusion is present within the section.

Overlying this part of the sequence is a mineralized unit, referred to here as the Marshall mineralized band, which has been the focus of base metal exploration for over fifty years. This horizon, its base metal deposits, and the alteration underlying it comprise the main focus of the present study. This sequence is composed of aphanitic to weakly quartz porphyritic fine-bedded to laminated volcaniclastic rocks with interdigitated sections of massive felsic material. This package of rocks is host to the most significant alteration and mineralization in the region. The "laminated cherty tuff" portions (Figure 26.6b) of this package host many of the massive to semi-massive sulphide occurrences (Figure 26.6c). No continuity of these laminated zones was mapped between the exposed mineralized sections, but this mineralized package can be traced for a strike length of over 1.5 km. This package of rocks represent a time period in which mineralization was actively taking place, possibly at or near several distinct horizons.

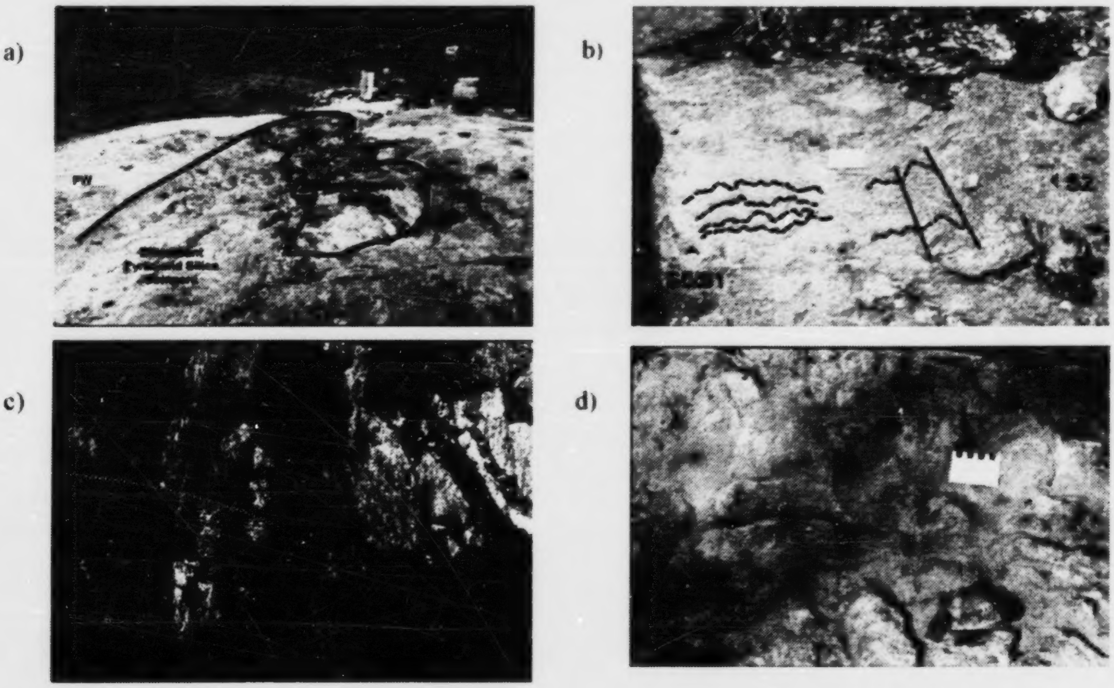

Figure 26.6. a) S-folded semi-massive sulphide pod with discordant alteration and mineralization in the footwall (FW - left side of photo). There is a sharp decrease in alteration intensity from the footwall to the hangingwall (HW). Adnarod Zone, looking east. **b)** Laminated cherty tuff at North Diabase Zone showing S0/S1 bedding and foliation folded by D2 deformation and overprinted by S2 foliation. Looking northeast, photocard for scale. **c)** 15 cm wide semi-massive zone of stratiform sphalerite and chalcopyrite in laminated pyritic tuff, North Diabase Zone. Pocket knife for scale (arrow), looking southwards. Top of photo rotated to left. **d)** Selective replacement by biotite-cordierite alteration in dacite tuff. Note the positive weathering nature of the less altered tuff remnants. North Diabase Zone, photocard for scale, looking east.

Above this mineralized and altered sequence is a sequence of relatively unaltered, medium-bedded to laminated tuffaceous rocks. These vary in grain size from ash to fine lapilli, and locally exhibit a crude normal gradation that indicates the younging direction is to the east. These tuffaceous rocks are the uppermost volcaniclastic unit within the Marshall tuff sequence. A weak, diffuse garnet-amphibole alteration and sections of discordant aluminosilicate alteration are widespread within this package of rock.

ALTERATION

Three principal types of alteration are present in the volcanic strata underlying the base-metal mineralization: biotite-cordierite, sericite-aluminosilicate, and silica-sericite. Together, these alterations outline a broadly discordant zone of hydrothermal alteration underlying the base-metal mineralization (*see* Figure 26.5). The mineralogy of these alteration assemblages is not primary, as a consequence of syntectonic regional amphibolite-facies metamorphism, but does reflect the bulk chemistry of the alteration.

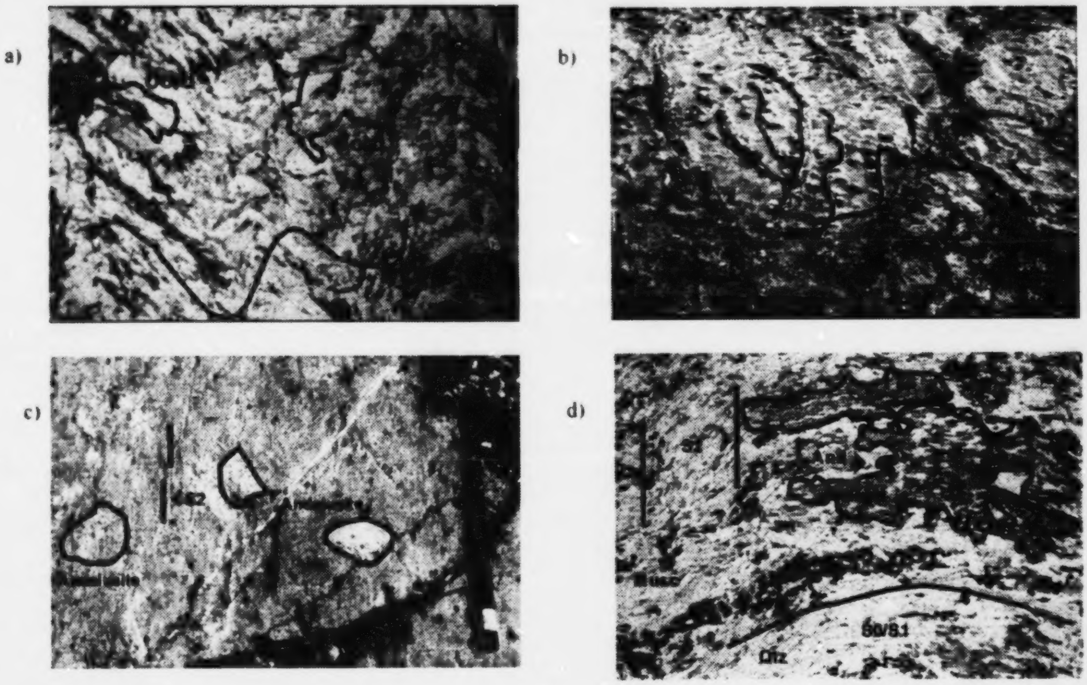

Figure 26.7. a) Photomicrograph of biotite-cordierite alteration. Pleochroic halos occur around zircon inclusions within cordierite grains. Field of view 10 mm, 2.5× magnification, plane polarized light. **b)** Porphyroblasts of andalusite disseminated along alteration fractures in biotite-cordierite altered dacitic tuff. Note the bleached margin surrounding the fractures containing the andalusite blasts signifying the development of sericite and the stripping of iron and magnesium. Footwall to Main Zone sulphide occurrence, pencil for scale (arrow), looking east. **c)** Large, centimetre size, subhedral megablasts of andalusite in an S2-foliated matrix of sericite and quartz. Adnarod Zone, pencil for scale, looking eastwards. **d)** Photomicrograph of megablastic andalusite porphyroblast in foliated sericite and quartz schist openly folded by D2 deformation. Field of view 6 mm, 4× magnification, plane polarized light.

Biotite-cordierite alteration is the most widespread of all alterations mapped in the area, and represents a broad discordant to slightly semi-conformable alteration zone. The alteration occurs as a semi-pervasive to pervasive replacement of the metavolcanic sequence underlying the mineralized package. The morphology of this alteration varies from fracture-controlled to pervasive. Replacement textures are well preserved as seen in Figures 26.6d and 26.7a. The alteration assemblage is now represented by a metamorphic mineral assemblage consisting of biotite, cordierite, sericite, quartz, and minor garnet. Accessory mineral phases such as actinolite, chlorite, and magnetite are restricted in their distribution and are not representative of the complete alteration system. Biotite-cordierite alteration is strongest in the footwall volcanic rocks underlying the mineralized sequence, and rapidly decreases in intensity above the uppermost portions of the mineralized package. At a select few locations, namely those associated with well-developed mineralization, the biotite alteration is associated with disseminated blasts of andalusite (Figure 26.7b).

Sericite-aluminosilicate (sericitization) alteration consists of 5–10% disseminated blasts of andalusite often in a foliated matrix of sericite, and represents a metamorphosed aluminous alteration. Based on the distribution of andalusite within the biotite alteration envelope, the alteration appears to define a discordant zone that extends from the southwest portion of the map area up to and including the mineralized package. The andalusite within this zone occurs as aligned blasts forming a stockwork or network of anastamosing sericite-andalusite filled fractures. Locally this style of alteration grades into larger zones of megablastic andalusite in a foliated matrix of sericite (Figures 26.7c and 26.7d). This alteration assemblage is present at or near each occurrence of stratabound mineralization, as well as some occurrences of stringer mineralization.

Silica-sericite alteration is mainly composed of silica and lesser amounts of sericite and sulphide. The alteration occurs as both discordant zones, and as a diffuse pervasive replacement of the volcaniclastic rocks. The most intense style exhibited by this alteration is the formation of laminated siliceous tuffaceous units known as the laminated cherty tuff (*see* Figure 26.6b). Some of these sections of the laminated cherty tuff may be exhalative, whereas others display textures that are indicative of replacement of a pre-existing unit. Sericite is not always present in the most intensely altered zones but forms a halo with silica around the margins of areas of intense pervasive silicification. The pervasive style of replacement occurs as large podiform zones with margins of decreasing alteration. These gradational contacts with the surrounding rocks are typically less than 1 m wide. This type of alteration is closely associated with the areas of stratabound and stringer mineralization. The laminated silica alteration/replacement is almost always the host to stratabound mineralization. Immediately below the main mineralized package and the laminated cherty tuff, silica and sericite form well-constrained zones of replacement. These zones commonly occur as both discordant zones and as selective replacement along primary lithological contacts. Most often the sulphide minerals within these altered areas form zones of weakly mineralized rock. Mineralization in this style of alteration typically occurs as disseminations and fracture fillings.

MASS CHANGE CALCULATIONS

The present focus of the current study is to chemically quantify and fingerprint each hydrothermal alteration assemblage in these rocks through the use of mass balance calculations outlined by MacLean (1990), MacLean and Kranidiotis (1987), and MacLean and Barrett (1993). This technique of lithogeochemical analysis is based on the conservation of immobile elements within the altered units. Elements which are immobile during hydrothermal alteration are residually enriched during net mass loss and diluted during net mass gain (MacLean 1990). In a single precursor system, binary plots of magmatic incompatible elements produce linear trends that contain the precursor composition and extend through the origin. Addition of elements during alteration results in a shift of the ratio towards the origin, and a loss of elements results in a shift away from the precursor composition along a common alteration line (MacLean and Kranidiotis 1987; Figure 26.8).

Chemical mass gains and losses were calculated from a precursor composition of 100 wt. % of anhydrous sample, using the established immobility of Zr as a monitor. The residual mass of a sample after alteration is calculated using the ratio of Zr in the precursor sample and the amount of Zr in the altered sample. The sample is then recalculated to the constant concentration of the immobile element (Figure 26.9). This calculation is computed for each element (component) of the sample via the following expression:

$$\text{R-C} = \%\ \text{component}_{\text{(altered rock)}} * \text{I-M}_{\text{(precursor)}}/\text{I-M}_{\text{(altered rock)}}$$

where R-C = reconstructed composition and I-M = immobile element monitor. The precursor mass is then subtracted from the reconstituted mass for each element, and mass gains or losses are then calculated:

$$\text{Mass Change} = \text{R-C} - \text{Precursor Composition}\ .$$

Since the initial mass of the sample is taken as 100 units, mass additions and subtractions are equivalent to weight percent changes. Therefore the mass changes for each element are given as the absolute difference relative to the precursor (Barrett and MacLean 1994).

MASS CHANGES WITHIN THE MARSHALL TUFF

Selection of a least altered precursor unit within the Marshall tuff was based firstly on a visual absence of alteration minerals. Secondly, those samples not visibly altered were examined under the microscope and compared and contrasted with each other on a TiO_2 versus Zr plot (Figure 26.9). A tight cluster of least-altered precursor rocks was identified and selection of the single precursor was based on proximity to the altered units compared.

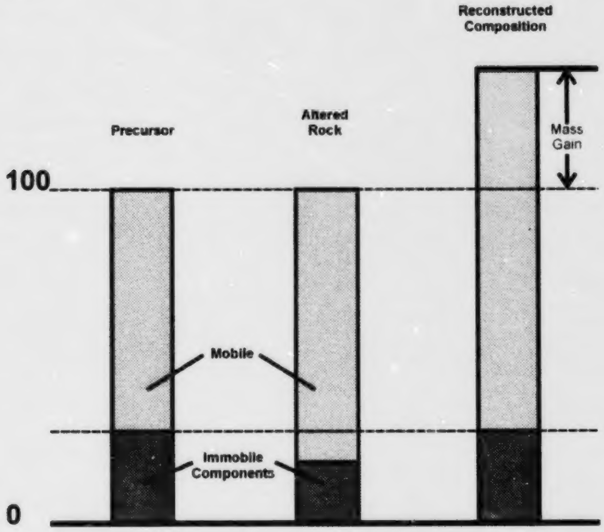

Figure 26.8. Illustration of mass change calculations for an altered rock sample based on 100 units of precursor, modified after figure 6 of MacLean and Barrett (1993).

The alteration system underlying base metal mineralization at Marshall Lake is characterized by a net mass gain. All alteration types have experienced a mass gain in both silica and alumina relative to the precursor unit. Individual alteration types vary in both the elements and their amounts gained or lost. The results shown in Figures 26.10a, 26.10b and 26.10c represent the average elemental mass gain or loss for each individual alteration type relative to the precursor. The biotite-cordierite alteration has undergone a net addition of Fe_2O_3, MgO and K_2O, Rb, Ba, and a net loss of Na_2O, CaO and Sr (*see* Figure 26.10a). Extensive leaching of CaO, Na_2O, Sr, and, to a lesser extent, Fe_2O_3 and MgO characterize the sericite-aluminosilicate alteration zone. K_2O, Rb, and Ba have been added to the system in significant amounts (*see* Figure 26.10b). As to be expected, the silica alteration zone has extensive addition of silica, and in some instances an addition of K_2O (*see* Figure 26.10c). An interesting note is that associated with each alteration is a progressive increase in the base metal content of each successive alteration type relative to the precursor.

Binary diagrams of elemental mass change such as ΔFe_2O_3+MgO versus ΔCaO+Na_2O and ΔK_2O versus ΔSiO_2 lend themselves to an easy illustration of possible mineralogical changes during hydrothermal alteration (Figures 26.11a and 26.11b). Mineralogically each alteration zone is characterized by the chemical gains and losses associated with its phase of hydrothermal alteration. The elemental gains and losses associated with the biotite-cordierite alteration assemblage are indicative of the breakdown of primary feldspar and, in the simplest case, the formation of a chlorite and sericite assemblage. Mass gains and losses associated with the sericite-aluminosilicate alteration assemblage are indicative of breakdown of both feldspar and any ferromagnesian minerals present, and the formation of both sericite, and possibly aluminous clay. The silicic alteration is indicative of a complete and wholesale replacement of the primary lithology by hydrothermal silica. The elevated presence of potassium associated with this alteration indicates a persistence of sericite in this alteration zone.

CONCLUSIONS

Mass balance calculations using immobile element ratios as outlined are useful in quantitatively estimating the chemical changes due to hydrothermal alteration of the volcanic pile at Marshall Lake. These calculations are an excellent tool to monitor chemical changes within an alteration system that serve as effective vectors to base-metal mineralization. Based on field relationships, mineralogical

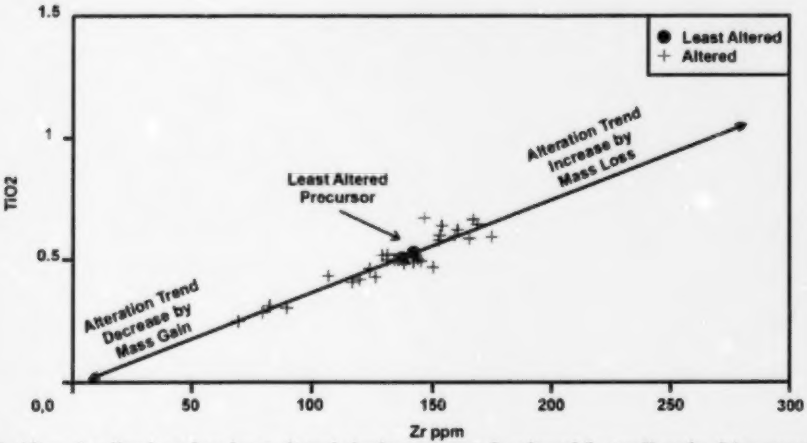

Figure 26.9. Alteration line based on least-altered single precursor for altered footwall rocks. Line passes through both the least altered samples and the origin. TiO_2/Zr ratio decreases during mass gain, resulting in a shift towards the origin. Conversely, during mass loss TiO_2/Zr ratio increases resulting in a shift away from the precursor position.

assemblages, and calculated chemical changes within the altered units at Marshall Lake, a paragenetic sequence of alteration is proposed as follows. An initial alteration of the precursor volcaniclastic rock to an assemblage now represented by biotite-cordierite enriched the rock in Al, Fe, Mg, and K and stripped the rock of Ca, Na and Sr. This process resulted in the generation of a pre-metamorphic alteration assemblage of chlorite and sericite. An increase in alteration intensity inwards within the alteration system results in the development of an assemblage of sericite and possibly aluminous clay. This aluminous assemblage is characterized by the removal of Ca, Na, Sr, Fe, and Mg, and the addition of Si, Al, K, Ba and Rb. Prograde hydrothermal alteration results in the silicification of the uppermost lithologies where there occurs almost complete replacement of the rock by quartz and the deposition of base-metal sulphide minerals.

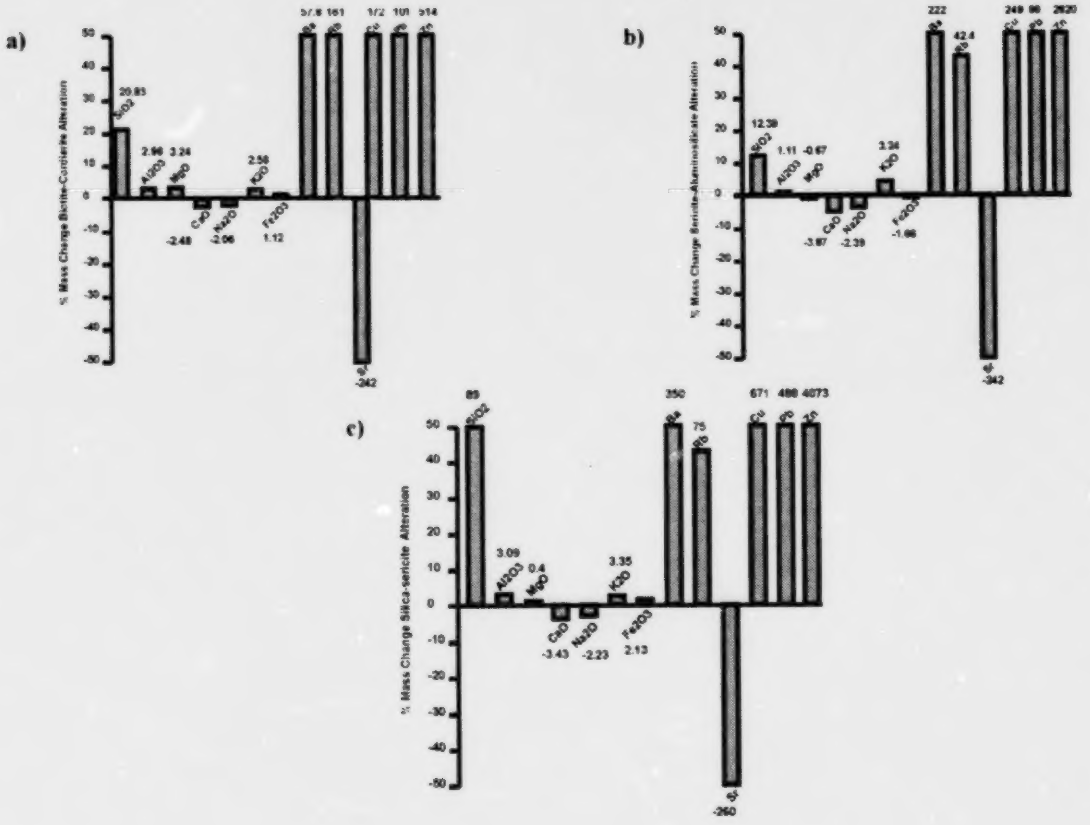

Figure 26.10. Histograms for mass gain and loss for the alteration facies at Marshall Lake. Mass changes are measured relative to a single least-altered precursor. **a)** Average gains and losses for the biotite-cordierite facies. **b)** Average gains and losses for the sericite-aluminosilicate facies. **c)** Average gains and losses for the silica-sericite facies.

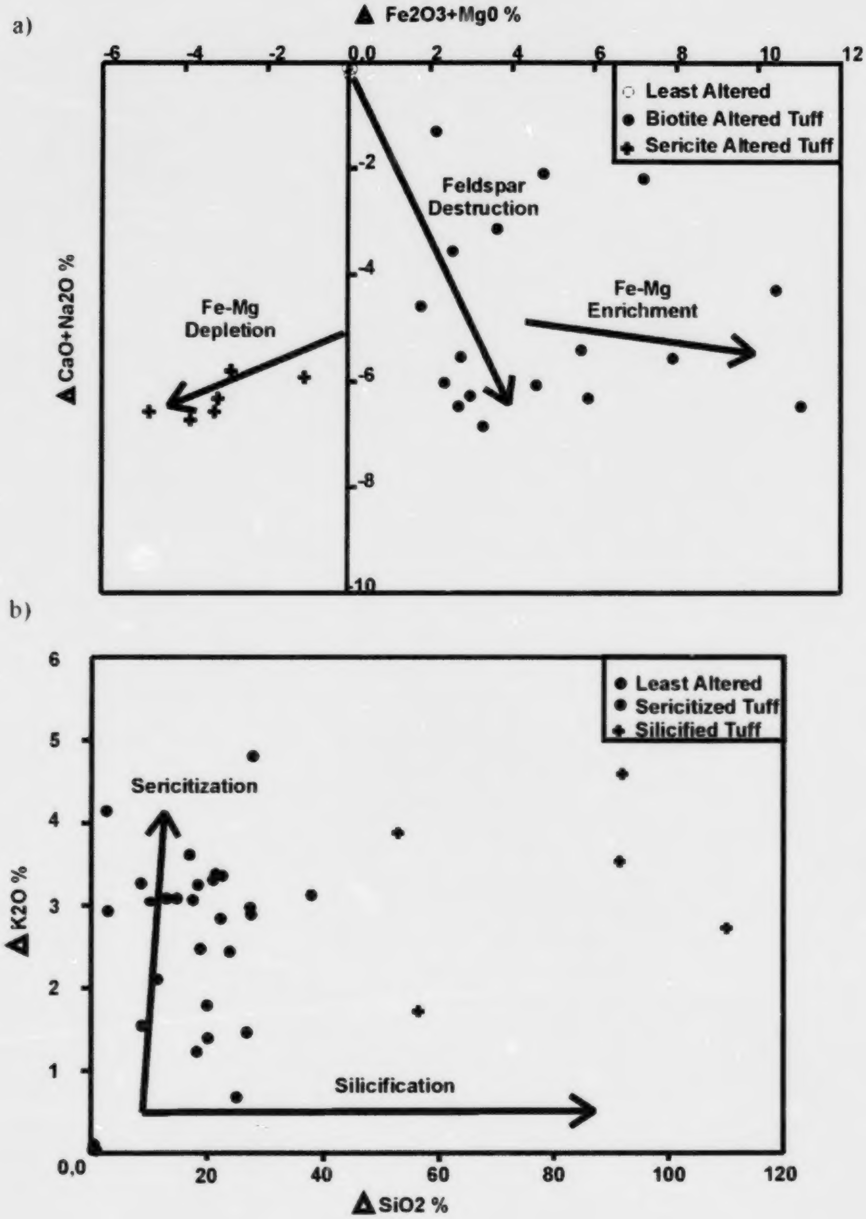

Figure 26.11. Calculated mass changes for footwall alteration zones at Marshall Lake. **a)** $\Delta CaO+Na_2O$ versus ΔFe_2O_3+MgO showing destruction of primary feldspar with addition of Fe_2O_3+MgO during biotite-cordierite alteration, and leaching of Fe_2O_3+MgO during sericitization. **b)** ΔK_2O versus ΔSiO_2 showing strong mass addition of K_2O during sericitization, and intense silicification.

ACKNOWLEDGMENTS

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27. Project Unit 99-025. Detailed Structural Studies in the Atikokan–Ignace Area, Northwestern Ontario

W.M. Schwerdtner[1] and S. Ahmad[1]

[1]Department of Geology, University of Toronto

INTRODUCTION

Exceptionally good exposure and road access characterize many clear-cut tracts of boreal forest in the Atikokan–Ignace area (Stone and Hallé 1996; Stone, Hallé and Chaloux 1998, 1999). Since 1999 we have been deriving much benefit from such exceptional conditions, while undertaking two field-based projects: 1) a geometric analysis of late-tectonic, pegmatite-aplite dike systems and 2) a lithologic and structural study of a modest-size granitoid batholith. Project 1 was started in 1999, as part of WST LITHOPROBE, and addresses the problem of whether the dike emplacement is associated with large-scale horizontal spreading of the Neoarchean crust. Project 2 commenced in June 2000, and will facilitate an attempt at establishing the dominant mode(s) of Archean batholith emplacement.

LATE-TECTONIC PEGMATITE-APLITE DIKE SYSTEMS (PROJECT 1)

Throughout the Irene–Eltrut Lakes complex and its vicinity (Schwerdtner et al. 1978, 1979), late-tectonic, pegmatite-aplite dikes abound in foliated to gneissic tonalite-trondhjemite-granodiorite (TTG) and associated, polydeformed amphibolite units. The dikes may be comagmatic with the 2.69 Ga, tabular White Otter and Cecil Lake plutons (Figure 27.1).

Some dikes are transected by widely spaced extension fractures (lenticular quartz veins), others furnish no conspicuous evidence of *in situ* deformation. The absolute age of dike emplacement is unknown, but will hopefully be found in 2001-2002 by zircon dating of aplite specimens.

Attitudes of several thousand dikes were obtained in 1999, mainly in study corridors along the two highways (Figure 27.1) or major lumber roads, and the data processed after the field season. In addition, we determined the attitude of displacement-difference vectors (DDVs) for individual dikes or dike segments (Schwerdtner and Ahmad, 1999, fig. 16.2). For a variety of reasons, DDVs could be found only for about 10% of the dikes observed in the field.

The study corridors were divided into a number of subareas, and structural data evaluated in contoured stereoplots for individual subareas (Figure 27.2). Stereoplots for the dike normals have unimodal contour patterns in many subareas, whereby the mean orientation of the dikes varies from subhorizontal to subvertical. The tectonic significance of the variation between subareas and different structural sites remains to be found. In particular, we are trying to understand why the dikes in mid-portions of oval gneiss structures, called "domes" in Figures 27.1 and 27.2, are dominantly subhorizontal (Owl Lake "dome") or dominantly subvertical (Dovetail Lake "dome", new and unprocessed field data). Perhaps the dikes postdate the creation of oval structures ("gneiss domes"), as well as the large, 2.69 Ga plutons.

Unequivocal evidence was found in this season, that well-exposed oval structures such as the Owl Lake and Side Creek "domes" are multi-order, noncylindrical folds rather than large-scale relatives of triaxial boudins. In particular, the shear strain sense on the fold-enveloping surfaces is incompatible with triaxial boudinage (heterogeneous horizontal spreading) of tabular, TTG gneiss masses. This result of our field work in 2000 strongly suggests that the oval structures predate the late-tectonic, pegmatite-aplite dikes, and helps to explain the variation in mean attitude of the dikes between oval gneiss structures.

MENNIN BATHOLITH (PROJECT 2)

In the summer of 2000, Ahmad focussed attention on the southeastern half of the Mennin Batholith (Figure 27.1; Schwerdtner et al. 1978, 1979), also known as Revell Batholith (Blackburn 1981). As with many large granitoid masses in northwestern Ontario (Ayres, Halden and Ziehlke 1991), the Mennin Batholith is composed mainly of undeformed intrusive phases, but also includes foliated to gneissic granitoid rocks. Detailed mapping has delineated narrow metavolcanic units (apparent screens or septa) within the undeformed bodies of individual phases. This points to piecemeal intrusion of thin magma sheets, and is difficult to reconcile with wholesale diapirism of granitoid magma (Schwerdtner, Crews and Moslehi 1998).

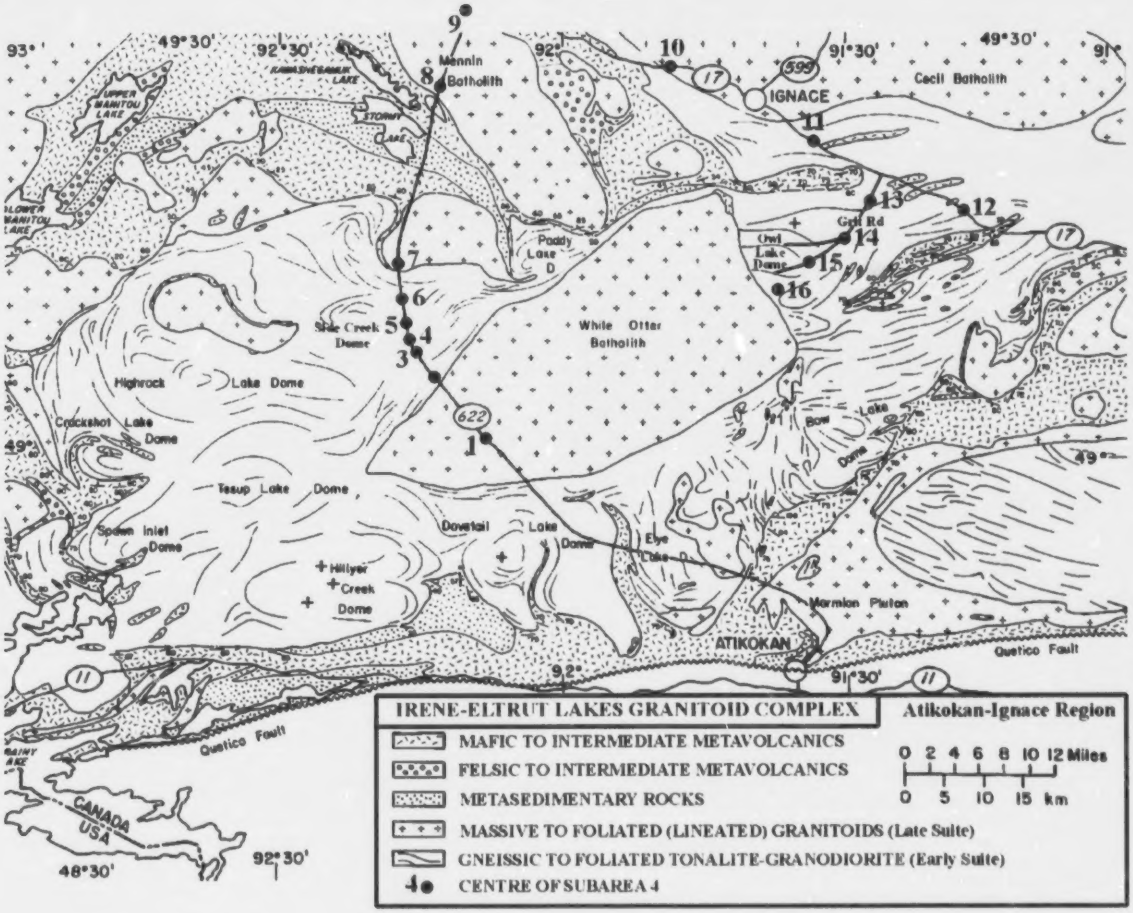


Figure 27.1. Structural map of the Atikokan–Ignace area showing the localities of subareas, (numbered 1-16), studied in the Irene–Eltrut Lakes granitoid complex and Mennin batholith. Each subarea consists of a series of outcrops located on the paved highways (#17 and 622) and on, or in the vicnity of, Grit Road, south of Ignace. Typically, the length of a subarea is 2 to 7 km (*modified from* Schwerdtner et al. 1979).

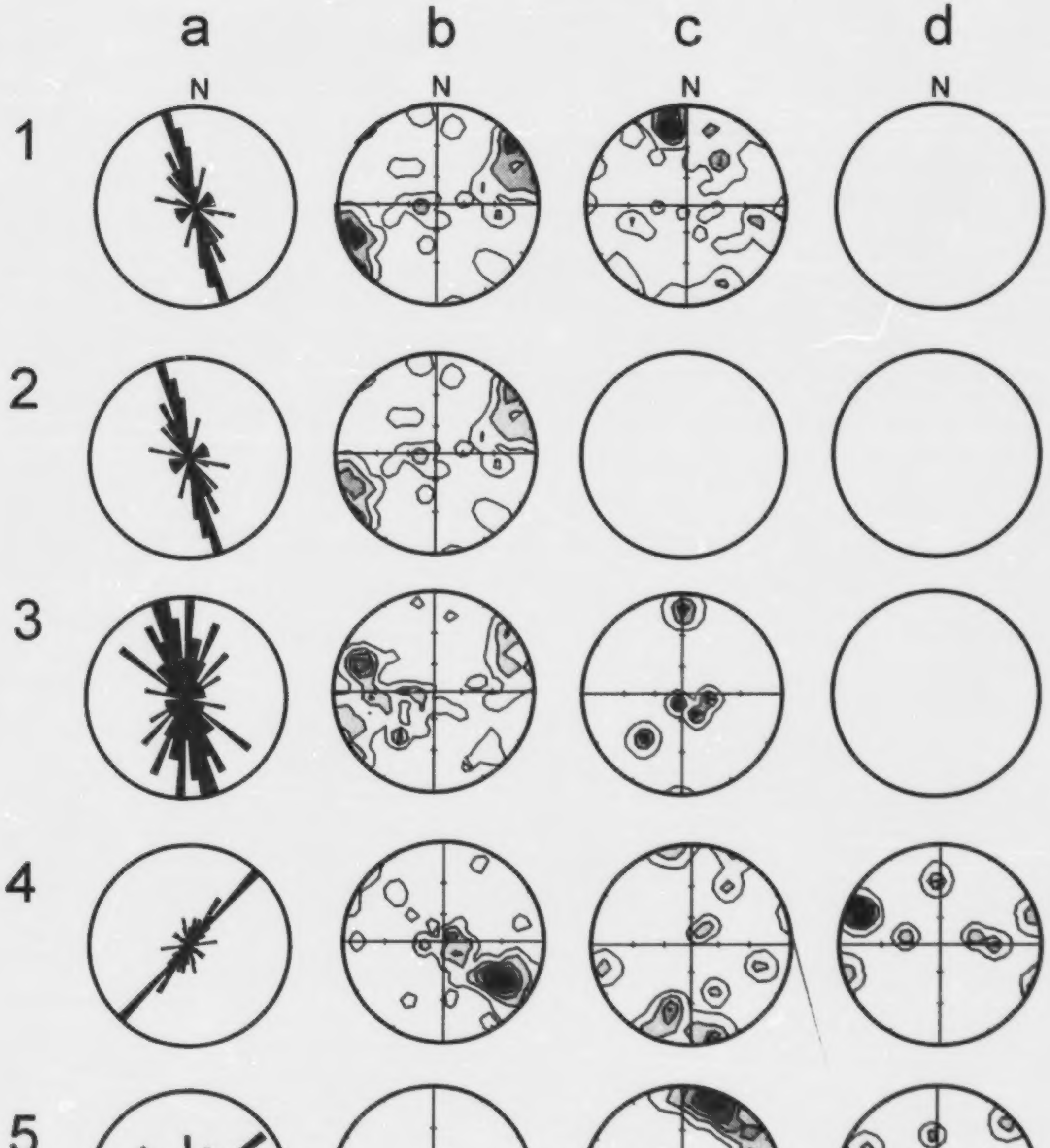
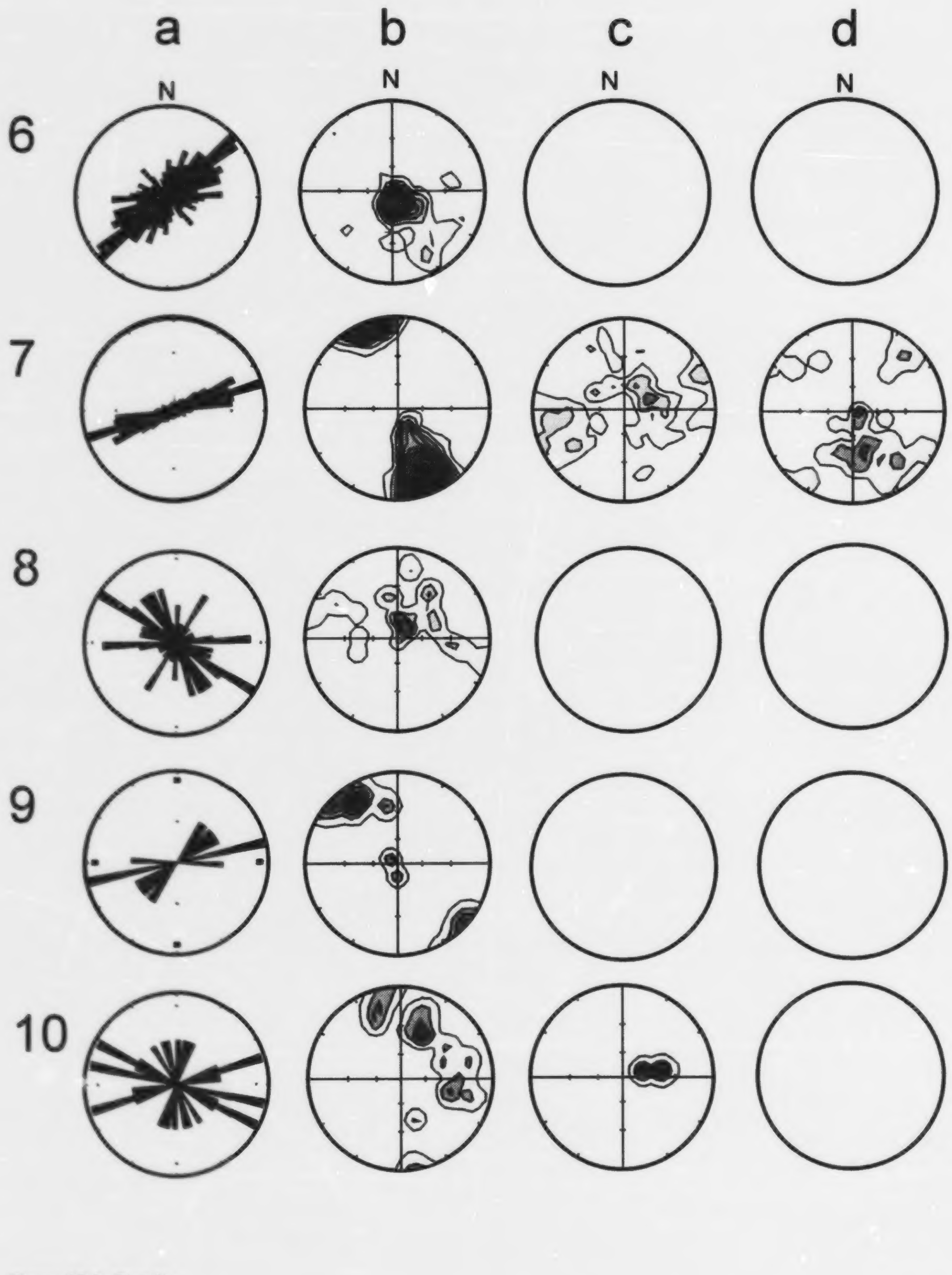


Figure 27.2. (Part 1)



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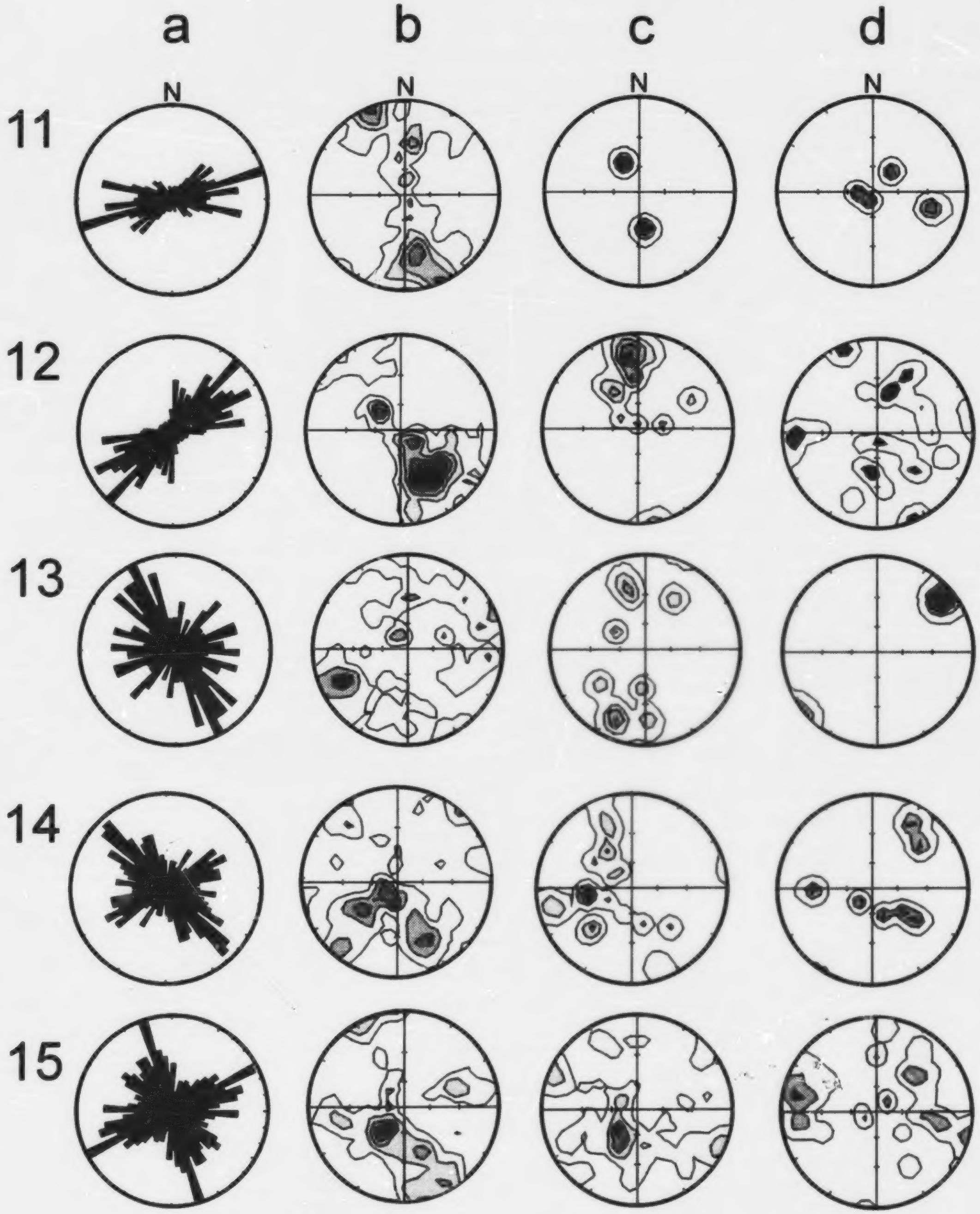

Figure 27.2. (Part 3)

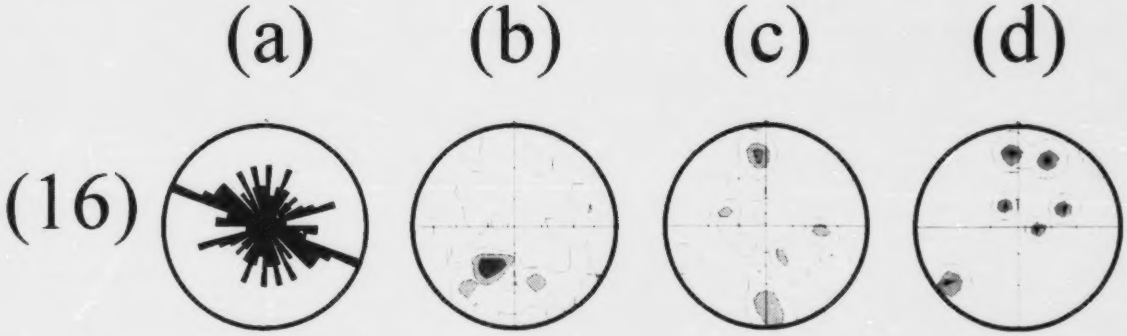

Figure 27.2. (Part 4)

Figure 27.2 (Parts 1, 2, 3 and 4). Columns (a), (b), (c) and (d) denote Figures 27.2a, 27.2b, 27.2c and 27.2d, respectively. Rows 1-16 denote subareas 1-16, respectively. (Subarea locations are shown in Figure 27.1). An empty plot in column (c) or (d) indicates that no data of this type were available for the given subarea. **(a)** Rose diagrams of the strike of dike segments per subarea. **(b)** Density-contoured, equal-area plots of dike normals per subarea. **(c)** Density-contoured, equal-area plots of normals to dilation planes, (only one displaced planar marker found in the wall rocks), per subarea. **(d)** Density-contoured, equal-area plots of the directions of displacement-difference vectors (DDVs), (two displaced planar markers found in the wall rocks), per subarea.

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28. Project Unit 99-07, 95-31 and 94-07. Variation in Crustal Level and Large-Scale Tectonic Controls on Rare-Metal and Platinum-Group Element Mineralization in the Southern and Grenville Provinces

R.M. Easton[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

An objective of the study of the Cu-Ni-PGE potential of the River Valley intrusion (Easton and Hrominchuk 1999; Hrominchuk, this volume) was to understand the character of the country rocks of the intrusion. Specifically, why did the Red Cedar Lake gneiss, abundant east of River Valley, apparently disappear west of River Valley? Addressing this question, as well as compiling the Ontario portion of the Tectonometamorphic map of the Canadian Shield (Easton 2000), has led to an improved understanding of the character, tectonics and mineral potential of Archean rocks found in the Superior, Southern and Grenville provinces in the Elliot Lake–Sudbury–North Bay area (Figure 28.1). This contribution provides an overview of these Archean rocks, and their influence on Proterozoic mineralization and localization of major tectonic elements, specifically, emplacement of the East Bull Lake intrusive suite.

PREVIOUS INTERPRETATIONS

Archean rocks in the southeastern Superior Province and beneath the Southern Province generally have been regarded as constituents of the Abitibi subprovince (e.g., Jackson and Fyon 1991); consisting mainly of the Ramsey–Algoma granitoid complex, plus a few small greenstone belts (e.g., Whiskey Lake, Benny, Temagami) (Jackson and Fyon 1991). In the southwestern Abitibi subprovince, the greenstone belts contain the oldest rocks, although U-Pb zircon ages are only available from the Temagami belt (*circa* 2736 Ma, Bowins and Heaman 1991). The Ramsey–Algoma granitoid complex consists of 3 gneiss domains (Ramsey, Algoma and Levack) and a plutonic domain (Figure 28.1), with the gneiss domains being older (2716-2711 Ma, Jackson and Fyon 1991). Apart from the Levack gneiss complex, most of the region underlain by the Ramsey–Algoma granitoid complex has not been mapped in detail.

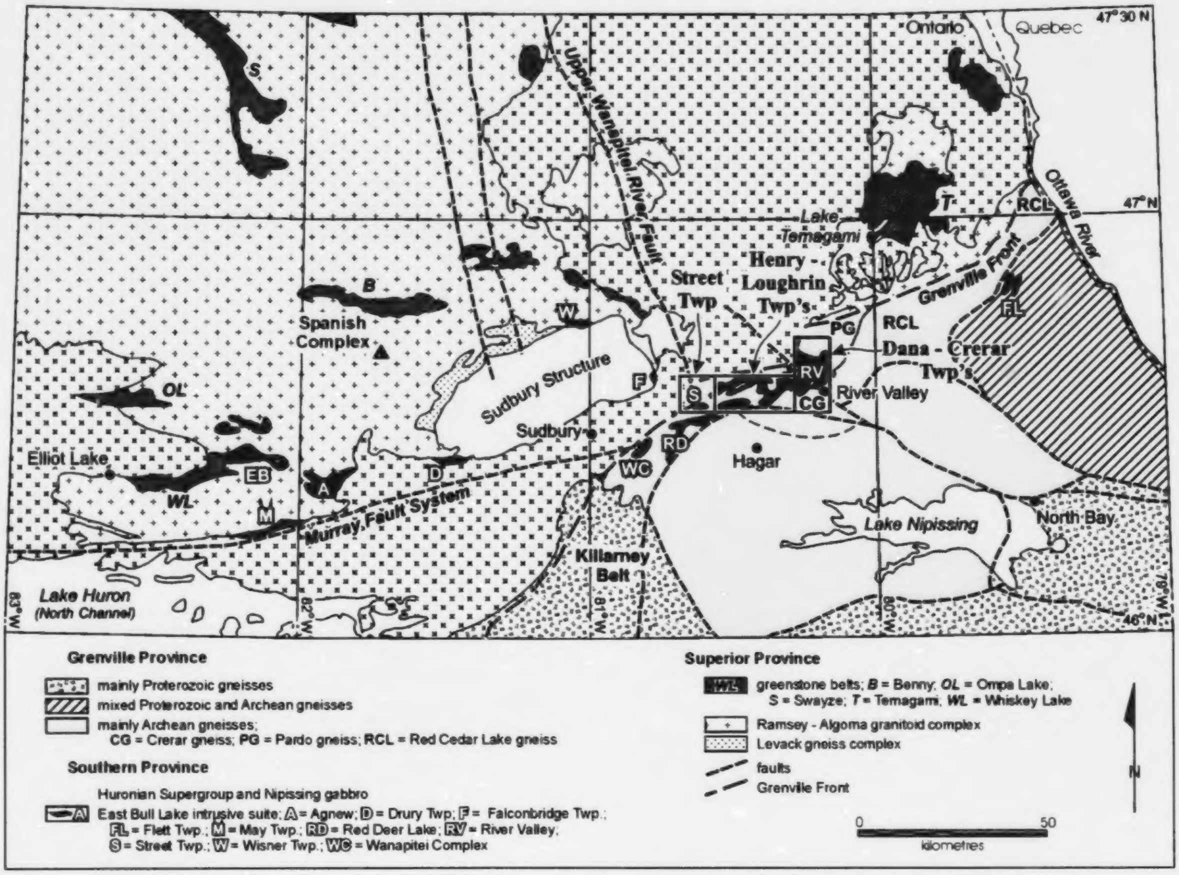
In contrast, Archean rocks in the Grenville Province south of Temagami, in particular, the Red Cedar Lake gneiss, have generally been equated with the Pontiac subprovince (e.g., Lumbers 1978; Easton 1992, Davidson 1998). If this interpretation is correct, then it suggests the presence of a subprovince boundary roughly coincident with the Grenville Front in the Temagami area. On the basis of Nd-Sm model ages (Dickin and McNutt 1989; Dickin 1998), Archean rocks are believed to constitute large portions of the Nepewassi, Tilden Lake and Tomiko domains in the Sudbury to North Bay portion of the Grenville Province (Figure 28.1). Except in the River Valley and Street Township areas (Easton and Hrominchuk 1999; Easton and Murphy 2000), the parts of the Grenville Province potentially underlain by Archean rocks have only been mapped at a reconnaissance level (Lumbers 1971a-c, 1973, 1975).

NEW OBSERVATIONS FROM THE RIVER VALLEY AREA

Easton and Hrominchuk (1999) tentatively identified four main gneissic units in the River Valley area, with two units restricted to the area north of the Sturgeon River (Pardo and Red Cedar Lake gneiss) and two units located south of the Sturgeon River (gneiss association III and IV). All these units are older than the 2475 Ma River Valley intrusion. On the basis of further study, including geochemistry, metaplutonic rocks of gneiss association IV can be correlated with similar rock units cutting the Pardo gneiss. In addition, rocks of gneiss association IV identified in the field as quartzite, on the basis of petrographic and geochemical analysis, are now interpreted to represent alkali feldspar granites that were hydrothermally altered by the River Valley intrusion and subsequently metamorphosed.

Pardo Gneiss and Related Metaplutonic Rocks

The Pardo gneiss lies directly north of the River Valley intrusion in Dana Township (Figure 28.1). It consists of two main components: 1) fine-grained biotite quartzofeldspathic gneiss (metagreywacke) cut by granodioritic to tonalitic leucosome veins, which constitute from 5% to 25% of the rock and


47°30 N
Ontario
Quebec
47°N
46°N
83°W
82°W
81°W
80°W
79°W
S
T
RCL
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W
OL
EB
WL
M
A
D
F
S
RV
CG
PG
RD
WC
FL
Upper Wanapitei River Fault
Ottawa River
Lake Temagami
Henry - Loughrin Twp's
Street Twp
Grenville Front
RCL
Dana - Crerar Twp's
River Valley
Spanish Complex
Sudbury Structure
Sudbury
Hagar
Elliot Lake
Murray Fault System
Lake Nipissing
North Bay
Killarney Belt
Lake Huron
(North Channel)
Grenville Province
mainly Proterozoic gneisses
mixed Proterozoic and Archean gneisses
mainly Archean gneisses;
CG = Crerar gneiss; PG = Pardo gneiss; RCL = Red Cedar Lake gneiss
Southern Province
Huronian Supergroup and Nipissing gabbro
East Bull Lake intrusive suite; A = Agnew; D = Drury Twp; F = Falconbridge Twp.;
FL = Flett Twp.; M = May Twp.; RD = Red Deer Lake; RV = River Valley;
S = Street Twp.; W = Wisner Twp.; WC = Wanapitei Complex
Superior Province
greenstone belts; B = Benny; OL = Ompa Lake;
S = Swayze; T = Temagami; WL = Whiskey Lake
Ramsey - Algoma granitoid complex
Levack gneiss complex
faults
Grenville Front
N
0
50
kilometres

Figure 28.1. Location map showing distribution of Archean rocks in the south-central Canadian shield in Ontario, as well as the distribution of rocks of the East Bull Lake intrusive suite. Proterozoic intrusive rocks within the Grenville Province have been omitted for clarity. *Modified from* Ontario Geological Survey (1992a, 1992b), Lumbers (1971a, 1973, 1975).

2) medium-grained, granodioritic to monzogranitic gneiss, possibly representing plutonic rocks that intruded the metasedimentary migmatite. Distribution of these two components shows considerable variation across the River Valley area. Individual plutons are difficult to outline, and it is possible that the plutonic component was emplaced as a series of sheets into the metasedimentary gneiss, leaving screens of varied size of the metasedimentary country rock. Non-migmatized metawacke and granodiorite occur directly north of the Grenville Front boundary fault in Pardo Township (Lumbers 1973), and likely represent equivalents of the Pardo gneiss preserved at higher structural levels.

Gneissosity and folds in the Pardo gneiss are cut by both the Matachewan and Sudbury dike swarms, the former indicating that the main migmatitic (and folding?) event affecting the Pardo gneiss occurred prior to 2445 Ma, and was likely Neoarchean in age. Effects of Grenville deformation and metamorphism are not apparent in the field; however, thin-section examination of both the Pardo gneiss and crosscutting Sudbury dikes indicate that the area underlain by the Pardo gneiss has been affected by high-grade metamorphism after 1240 Ma.

The Pardo gneiss is cut by pink- to white-pink weathering, fine- to medium-grained, gneissic to foliated, granitoid rocks. Lumbers (1973) classified these granitoid rocks as monzonite to quartz syenite; however, geochemistry suggests these rocks are more appropriately termed alkali feldspar granite using the normative classification of Streckeisen (1976). The alkali feldspar granites occur at the contact with the River Valley intrusion in parts of Dana and Crerar townships, and are peraluminous, with low total REE (less than 50 ppm), positive Eu anomalies (Eu/Eu* 7.9), and are corundum normative, suggesting an S-type affinity (Figure 28.2a). Breaks and Moore (1992) reported similar REE patterns from their Type 2 phase of the Neoarchean, peraluminous, S-type, Ghost Lake batholith in northwest Ontario (Figure 28.2a), and suggested that the unusual chemistry of these rocks resulted from feldspar accumulation.

Red Cedar Lake Gneiss

The Red Cedar Lake gneiss (Lumbers 1978; *see also* Easton 1992) crops out within the Grenville Front tectonic zone between River Valley and the Ottawa River (Figure 28.1). In the River Valley area, it consists of granular, granodioritic gneiss, that locally contains abundant fine-grained inclusions of quartzofeldspathic to amphibolitic composition. Easton and Hrominchuk (1999) suggested that the Red Cedar Lake gneiss represented a more flattened and cataclastic equivalent of the Pardo gneiss, perhaps due to an increase in the penetrative character of Grenvillian deformation. The geochemistry of the Red Cedar Lake gneiss is consistent with this suggested linkage to the Pardo gneiss (Figure 28.2b).

Crerar Gneiss Association

The Crerar gneiss association (gneiss association III of Easton and Hrominchuk (1999)), underlies most of southern Crerar Township (Figure 28.1), and is dominated by migmatitic, hornblende tonalitic to granodioritic gneisses. In general these gneisses are flattened, with leucosomes subparallel to gneissosity; locally, these rocks can be termed straight or transposed gneisses. The migmatitic hornblende gneiss unit locally contains 10 to 200 m wide zones of migmatitic amphibolite and calc-silicate layers. All are locally cut by a fine-grained to medium-grained, migmatitic, monzogranite gneiss, which forms sheet-like, semi-concordant bodies. Within the cores of regional folds, the gneiss is less flattened, and consists mainly of a potassium feldspar megacrystic granodiorite. In better exposed areas on the limbs of regional folds, the megacrystic rock becomes progressively deformed to form the flecky-textured, flattened, hornblende granodiorite gneiss typical of this unit. Geochemical data suggest the presence of at least 2 suites of granodioritic to tonalitic rocks within this gneiss association, consistent with the observations of Chen et al. (1995) on equivalent rocks near Hagar (Table 28.1). A sample of Crerar gneiss analyzed by Dickin (1998) gave a Nd-Sm model age of 2.73 Ga, and a $^{207}Pb/^{204}Pb$ ratio of 14.90. The latter was interpreted by

Dickin (1998) as indicating that the gneiss was subjected to strong uranium depletion during Archean metamorphism and thus represented a sample of deep-crustal Superior Province basement. Rocks of the Crerar gneiss association are also cut by metamorphosed Sudbury swarm dikes, but to date, no Matachewan swarm dikes have been observed cutting the Crerar gneiss association. The absence of Matachewan swarm dikes may reflect the fact that the Crerar gneiss association represents a deeper crustal level compared to the Pardo gneiss association (Figure 28.3).

Interpreted Geological History and Tectonic Setting

Geochronological data for the Hagar–River Valley–Temagami area are summarized in Table 28.1. Although the data are scattered and of varied reliability, they suggest that the Archean rocks in this area record a sequence of magmatic and metamorphic events similar to that observed in the Levack Gneiss complex, the higher-grade portions of the Quetico subprovince (e.g., Manitouwadge area), and the Ashuanipi subprovince in Quebec. Based on existing information, the sequence and timing of events does not indicate a linkage with the Pontiac subprovince, as had been suggested previously.

The following geological history is inferred. After deposition of a greywacke succession south of the Temagami greenstone belt, invasion by tonalitic to granodioritic plutons, probably accompanied by burial, formed the migmatitic gneisses now represented by the Pardo and Red Cedar Lake gneiss associations. These events likely occurred in a short interval, between 2685 and 2675 Ma. This was followed by a renewed period of tonalitic to granodioritic magmatism, deformation and regional metamorphism, possibly at mid-crustal levels, between 2670 to 2660 Ma. The Crerar gneiss association may represent the products of this event. Subsequent granitic to syenitic magmatism occurred between 2660-2640 Ma, and was accompanied by emplacement of pegmatite veins.

Interpreted Crustal Section in the River Valley Area

Percival et al. (1992) describe the general features of exposed crustal cross sections. A logical extension of this work is the interpretation of the 3 gneiss associations in the River Valley area as a southward-deepening section of the crust, as illustrated in Figure 28.3. Exposure of this section is likely

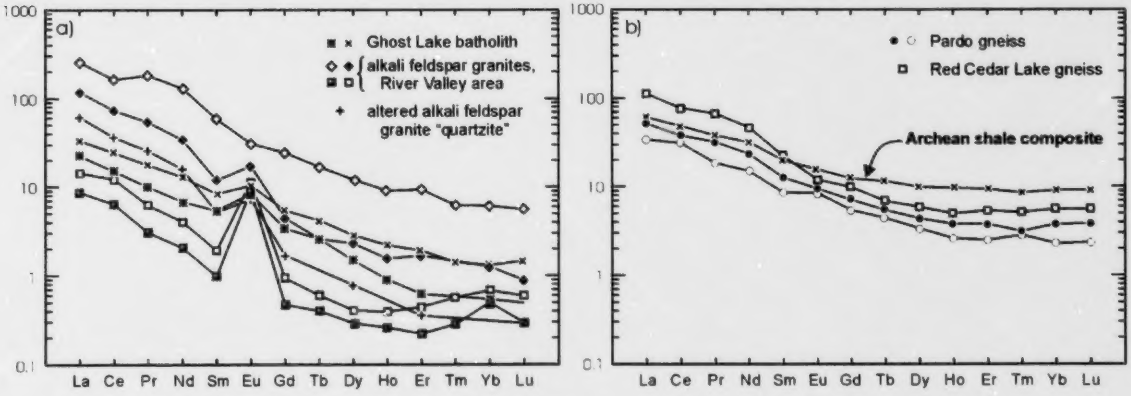

Figure 28.2. a) Chondrite-normalized rare-earth element plots for alkali feldspar granites cutting the Crerar and Pardo gneiss associations. Representative samples from Type 2 granites of the Ghost Lake batholith (Breaks and Moore 1992) are shown for comparison. **b)** Chondrite-normalized rare-earth element plots for rocks of the Pardo and Red Cedar Lake gneiss associations. Average Archean shale composite of Taylor and McClennan (1985) is shown for reference.

Table 28.1. Correlation chart for Archean metasedimentary and high-grade gneiss domains located in the central and southern Superior Province, Ontario and Quebec.

	Superior Province			**Southern-Grenville**		
Event	**Pontiac subprovince, Quebec-Ontario (metasedimentary)**	**Ashuanipi subprovince, Quebec (high-grade gneiss)**	**Quetico subprovince, Ontario (metasedimentary)**	**Elliot Lake area, Ontario (unknown type)**	**Levack Gneiss Complex, Ontario (high-grade gneiss)**	**Hagar-River Valley-Temagami area, Ontario (unknown type)**
syenite, ne-syenite	◆	2625±2[9] Ma	◆?	no data	◆?	no data
late, high-level granitic rocks	2632[16] Ma		◆?	no data	2642±1[3] Ma, Cartier Granite	
Migmatization	◆		◆?	no data	2647±2[1], ~2643[2] Ma	2647±12[7] Ma, (Ingall Lake batholith)
granulite facies metamorphism	◆		2650±2[13], 2651±3[13] Ma	2641 Ma, reset titanite[1]	2648±1[2] Ma	
Pegmatite	◆		2653^{+3}_{-4}[12] Ma	no data	no data	2650±4[5], 2660[6] Ma
Monzodiorite, syenite, ± ne-syenite	◆	2660±1, 2670±2[8] Ma	2671±2[12], 2665±2[12], 2677±5[17] Ma	2665±2 Ma, Parisien Lake syenite[1]	2657±3[2] Ma	younger than migmatization of tonalite and paragneiss
Pegmatite	~2668[15], 2663±1[15] Ma	◆	◆	◆	◆	◆
Synmetamorphic tonalite-granodiorite plutonism	◆	2682±5, 2669[8] Ma	2669±3[11] Ma	2676±11[18]	2681-2669[2] Ma	2669±4[4] Ma (Tilden trondhjemite)
Migmatization and/or granulite facies metamorphism	~2665-2677 Ma	2668±1[8], 2682^{+5}_{-3}[8] Ma	2665-2680[11, 12] 2661±1[13] Ma	no data	2661±1[2] Ma	no data
Monzodiorite, syenite, pegmatite	2685±3[15], 2681±2[15], 2680±1[15], 2686[16], 2678[16], 2669[16] Ma	◆	◆	◆	◆	◆
tonalite-granodiorite plutonism	2673±4[15] Ma to 2695±2[15] Ma	~2690[8], inheritance 2.8-2.7 Ga	2688±4[14], 2689±2[11], 2687±19[12] Ma	no data	2681-2669[2] Ma	2678-2683[4] (Warren trondhjemite)
early tonalite-granodiorite plutonism	◆?	◆?	◆?	2697±12[18]	2711±7[1] Ma	2730±2[4] Ma (Ingall Lake batholith)
youngest detrital zircon in paragneiss	2698, 2696, 2694, 2688, 2687, 2677[15, 10] Ma (Pontiac, Cadillac, Timiskaming groups)	<2700[8] Ma	2690, 2692[10, 11], 2687[12] Ma	not applicable?	not applicable	no data
Paragneiss provenance	3029, 2980, to 2760, most <2725[15, 10] Ma	3.3-2.7[8] Ga	3.35, 2.9, 2.7[14, 12] Ga	not applicable?	not applicable	no data

[1] Krogh et al. 1984, [2] Card and Wodicka in press, Wodicka and Card 1995, [3] Meldrum et al. 1997, [4] Chen et al. 1995, [5] Krogh 1994, [6] Krogh and Davis 1970, [7] Steiger and Wasserberg 1969, [8] Percival et al. 1992, [9] Machado and Cheve 1991, [10] Davis 1992, [11] Zaleski et al. 1999, [12] Percival and Sullivan 1988, [13] Pan et al. 1998, [14] Davis et al. 1990, [15] Mortensen and Card 1993, [16] Machado et al. 1991, [17] Kwon et al. 1989. [18] Prevec 1993 ◆ event not present, ◆? event may not be present.

the result of north-northwest directed transport along Grenville-age thrust faults. As interpreted herein, Archean metawackes exposed immediately north of the Grenville Front represent high-levels of the crust. Rocks of the Pardo gneiss, immediately south of the Grenville Front, represent the middle to lower part of a 10 to 15 km thick upper crustal layer dominated by supracrustal and moderate- to high-level intrusive rocks. Rocks of the Red Cedar Lake gneiss would represent the basal portion of this upper crustal layer. Tonalitic to granodioritic rocks of the Crerar gneiss association represent part of a 10 to 15 km thick middle crustal layer. This crustal section would be roughly equivalent to the section observed from west to east across the Wawa gneiss domain of the Superior Province (e.g., Moser et al. 1996).

REGIONAL OBSERVATIONS

Archean Rocks in the Street Township Area

The presence of extensive tracts of Archean rocks in Street Township is inferred from two observations. First, migmatitic granites within the township contain inclusions of East Bull Lake intrusive suite rocks, and the granites have yielded a U-Pb zircon age of $2475^{+25}/_{-10}$ Ma (Corfu and Easton 2000). Relative age

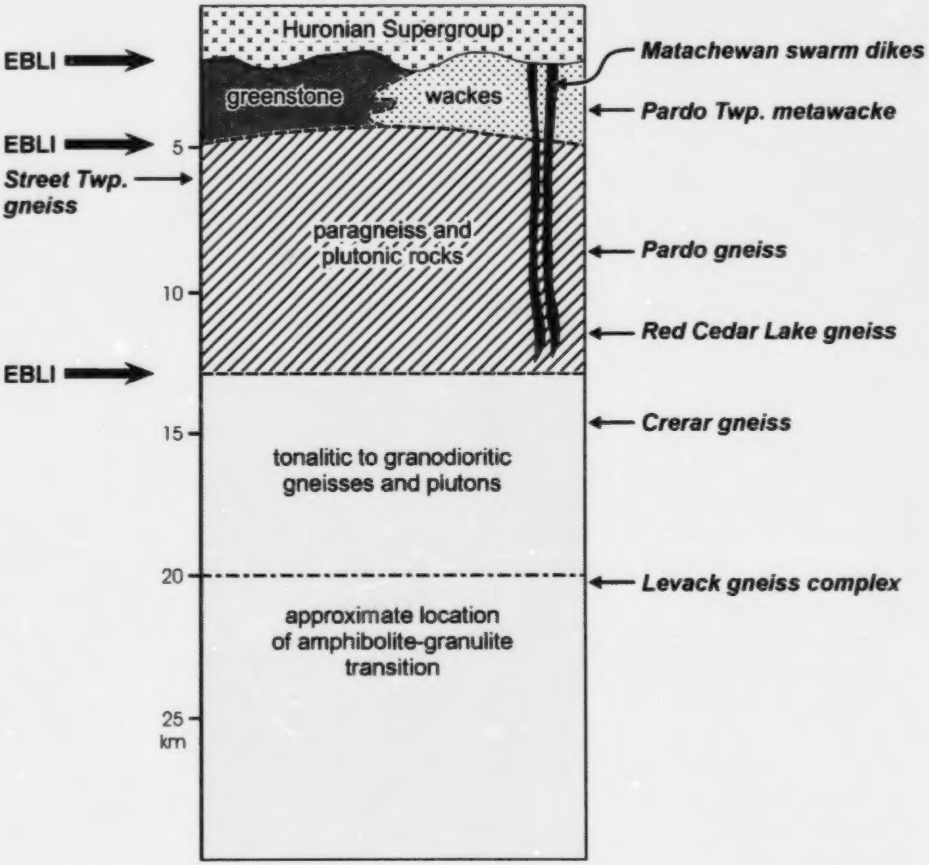

Figure 28.3. Cartoon illustrating exposed crustal section in the River Valley area. Possible emplacement levels for rocks of the East Bull Lake intrusive suite are illustrated (*see* text for discussion). Current data from the River Valley area suggest emplacement of the River Valley intrusion into the Pardo gneiss.

relationships suggest that these migmatitic granites are among the youngest units present within the Grenville Front tectonic zone in Street Township (Easton and Murphy 2000). Second, migmatitic garnet amphibolite gneisses in Street Township are intruded by non-migmatitic rocks correlative with the East Bull Lake intrusive suite (Easton 1999), indicating that a high-grade metamorphic event occurred prior to *circa* 2475 Ma. Unlike the River Valley area, however, the Archean rocks are dominantly mafic, although some metasedimentary gneisses are also present (Easton and Murphy 2000). The compositional differences between the gneisses in Street and Dana townships may simply reflect the fact that high-grade metamorphism affected a volcanic-dominated sequence in Street Township, whereas a sediment-dominated sequence was present in Dana Township. If so, then the two areas may represent a broadly similar exposure level within the crust. This would be consistent with the occurrence of the River Valley intrusion throughout the area between Street and Dana townships.

Archean Rocks North of Sudbury

The granulite-facies Levack gneiss complex, located between the 1850 Ma Sudbury Igneous Complex and the Benny greenstone belt, contains metaplutonic rocks ranging in age from 2711 to 2647 Ma, with granulite facies metamorphism occurring between 2647 Ma and 2642 Ma (Ames et al. 1997) (Table 28.1). P-T conditions of the granulite-facies event are 6 to 8 kbar and 750 to 800°C, with local amphibolite facies retrogression to 2 to 3 kbar and 500 to 550°C (James et al. 1992) occurring adjacent to the 2642±1 Ma, post-metamorphic, Cartier granite (Meldrum et al. 1997) that intruded the Levack gneiss complex. Within 2 km of the Sudbury Igneous Complex, a second metamorphic event at 1850 Ma overprints the granulite facies rocks, with reported conditions of 4 to 6 kbar and 800 to 950°C (James et al. 1992). In terms of Pb isotopic signature, the Levack gneiss complex shows a similar depletion of uranium as that observed in the Crerar gneiss association (cf. Dickin 1998).

Percival et al. (1992) interpreted the region between the Levack gneiss complex north to the Benny greenstone belt as a crustal section from mid- to lower-crust that was exposed by the Sudbury event. Card (1994) concurred, but suggested that exhumation occurred mainly in the Neoarchean, in part because the Levack gneiss complex is cut by Matachewan swarm dikes. Ames et al. (1997), based on a U-Pb and Ar-Ar cooling age study of the Levack gneiss complex, suggested a two-stage exhumation history, a late Neoarchean uplift from 18-24 km to 6-9 km associated with emplacement of the Cartier granite, with final unroofing occurring during the 1850 Ma Sudbury event. Ames et al. (1997) noted that the timing of plutonic and metamorphic events within the Levack gneiss complex is similar to that observed in the Kapuskasing structural zone. What differs between the two areas is their exhumation history, with the Levack gneiss being uplifted to higher crustal levels very soon after peak metamorphism, possibly due to crustal extension, whereas uplift of the Kapuskasing structural zone occurred much later, perhaps in the Paleoproterozoic, along a listric thrust fault (e.g. Percival and West 1994).

A paired areomagnetic and bouguer gravity anomaly occurs north of the Benny greenstone belt and east of the Swayze greenstone belt, as shown in Figure 28.4a. In granitoid and gneissic domains elsewhere in the Superior Province, such paired anomalies are typically associated with higher-grade metamorphic rocks (upper amphibolite to granulite transition) (Easton 2000).

Archean Rocks in the Elliot Lake Area

Archean rocks in the Elliot Lake area consist of the greenschist to middle amphibolite facies Whiskey Lake and Ompa Lake greenstone belts, and a variety of plutonic rocks, ranging from foliated tonalite to massive monzogranite and syenite plutons (cf. Rogers 1992, 1993; Prevec 1993; Jensen 1994). In the Batchawana greenstone belt, further to the west, metamorphism occurred around 2674±3 Ma and 2668±2 Ma,

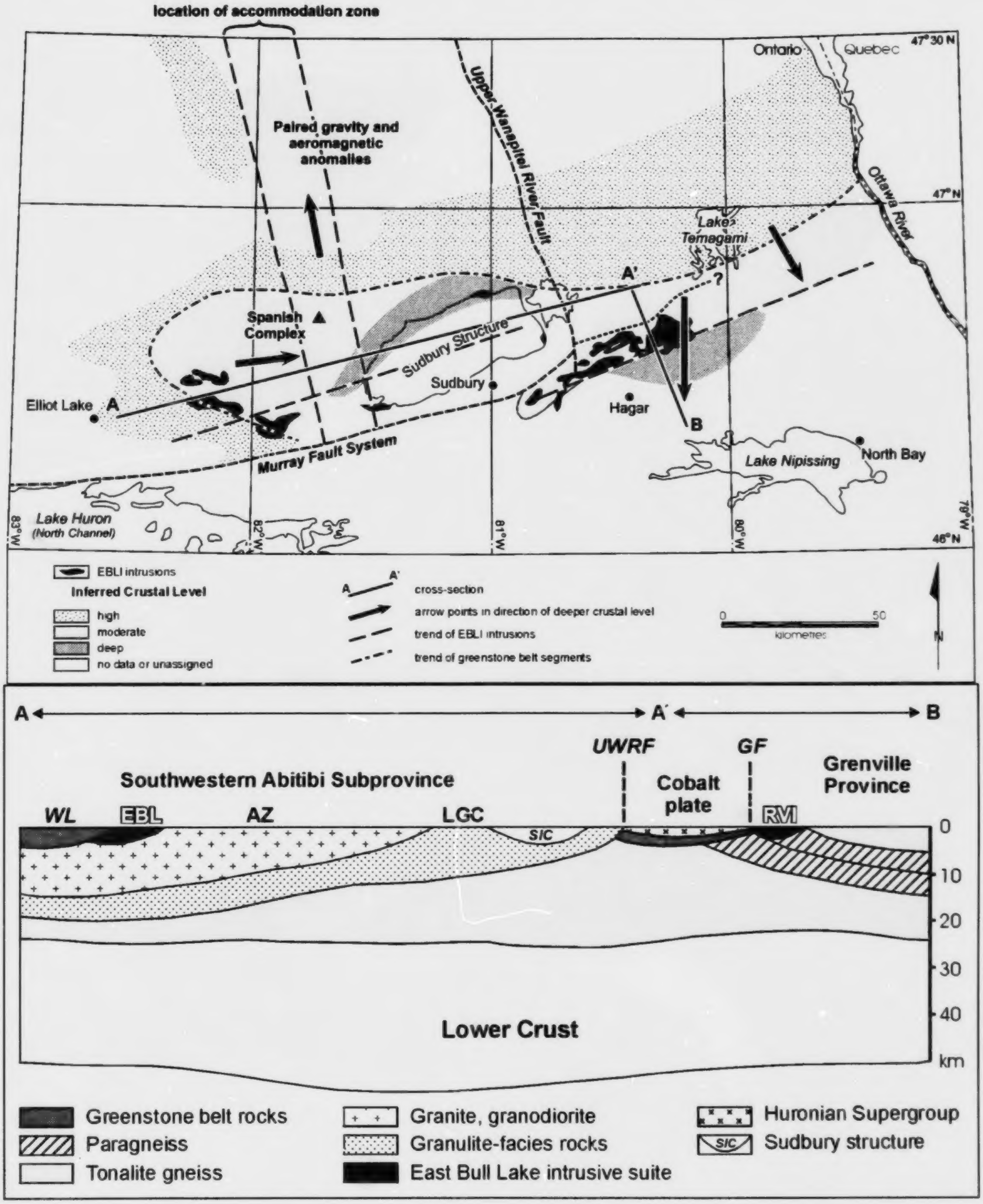

Figure 28.4. A) Interpretative map showing current exposed crustal levels of Archean rocks in the south-central Canadian shield. Arrows point in the direction of increasing crustal depth. Location of cross-section is indicated. **B)** Interpretative cross-section from Elliot Lake to Sudbury to River Valley showing relationships between main rock units. Abbreviations: AZ = accommodation zone; EBL = East Bull Lake intrusion, GF = Grenville Front, LGC = Levack gneiss complex; RVI = River Valley intrusion; UWRF = upper Wanapitei River fault; WL = Whiskey Lake greenstone belt.

based on a metamorphic titanite age and the age of a post-metamorphic pluton (Corfu and Grunsky 1987). This age range is similar to that for M_2 metamorphism within the central Abitibi subprovince (Easton 2000). Volcanic rocks in the Whiskey Lake and Ompa Lake greenstone belts are undated, but zircon from foliated and non-foliated granitoid rocks near the East Bull Lake intrusion give U-Pb ages of 2697±12 and 2676±11 Ma, respectively (Prevec 1993). The Archean basement in the Elliot Lake area represents a typical greenstone-granite terrane, and consequently, a relatively high crustal level. Even so, titanite from the 2665±2 Ma Parisien Lake syenite yields an age of 2641 Ma (Krogh et al. 1984), similar to the age of Levack gneiss complex metamorphism and Cartier granite emplacement, indicating that Archean rocks in this area locally record events that were more intense at deeper crustal levels.

REGIONAL SYNTHESIS

Figure 28.4a is an attempt to relate the disparate rock associations and inferred crustal levels into a coherent regional framework. The north-trending Upper Wanapitei River fault (Buchan and Ernst 1994) (Figure 28.4a) apparently divides the Archean rocks in the Elliot Lake to North Bay area into two domains. The eastern domain, which includes the River Valley–Hagar area, consists of supracrustal and metaplutonic rocks, with deeper levels in the crust being exposed, likely due to Grenville orogenesis, to the south. In contrast, the western domain is pluton dominated, with deeper levels of the crust, being exposed to the east. The Upper Wanapitei River fault has had a protracted deformation history, exhibiting at least 7 to 8 km of left-lateral movement between 2170 and 1850 Ma (Buchan and Ernst 1994), and at least 3 km of left-lateral movement post-1040 Ma (Easton and Murphy 2000). The amount of vertical movement across the fault is unknown. Significant vertical movement would be necessary to juxtapose granulites of the Levack gneiss complex against higher-crustal-level rocks to the east; however, if the Upper Wanapitei River fault re-activated an older listric fault system, then considerably less relative uplift across the fault may be present. As shown in the cross section in Figure 28.4b, the precursor to the Upper Wanapitei River fault may have been a listric fault, displaying a similar geometry to the boundary faults along the eastern flank of the Kapuskasing structure. Such a geometry would explain the exhumation of the Levack gneiss complex. This interpretation does not preclude the suggestion by Percival et al. (1992) that a crustal section is exposed between the Benny greenstone belt and the Levack gneiss complex. In addition, it may also provide an explanation for the location of the *circa* 1850 Ma Spanish River carbonatite complex, as well as north-trending faults that outline the eastern margin of the Swayze greenstone belt to the north of the carbonatite complex. It is speculated that the carbonatite complex and the faults to the north reflect an accommodation zone that developed as a consequence of Mesoproterozoic sinistral movement along the Upper Wanapitei River fault. In addition, post-1850 Ma uplift of the area between this accommodation zone and the Upper Wanapitei River fault would account for the limited preservation of Huronian Supergroup rocks north of the Murray fault in the Sudbury area, compared to areas to the west and northeast (Figure 28.1, 28.4b).

An east-trending, discontinuous line of greenstone belts (Benny, Temagami) lies to the north (Figure 28.4a). Are these belts exposed here simply as a consequence of a general northward increase in crustal level, or do they lie along a cryptic discontinuity that separates a high-crustal-level granite-greenstone terrane in the north from a deeper-crustal level granite-gneiss-migmatite terrane(s) to the south? In the east, the location of such a discontinuity would be roughly coincident with the location of the Grenville Front, and thus, would likely be difficult to document. North of Sudbury, the discontinuity either could be stitched by the 2642 Ma Cartier granite, or it could be coincident with the Benny deformation zone located between the Cartier granite and the Benny greenstone belt (Card 1994). Insufficient data are present north of East Bull and Agnew lakes to determine if a major discontinuity is present. The occurrence of a major crustal boundary could be critical with respect to emplacement of the East Bull and Agnew lake intrusions, as such a boundary could have served as a conduit for magma transport.

DISCUSSION – IMPLICATIONS FOR MINERAL EXPLORATION

Mineral deposits associated with major regional structures consist of shear-hosted gold deposits, rare-metal pegmatites and mineralization associated with high-volume magma systems (e.g., Cu-Ni, PGE) (e.g., Fyon et al. 1992a, 1992b; Breaks et al. 1999). Mineral deposits associated with deeper crustal levels include rare-metal pegmatites (e.g. Smeds 1994; Breaks et al. 1999). The next section discusses how the analysis of exposed crustal levels and regional structure herein relates to mineral exploration.

Rare Metal Pegmatites

In northwest Ontario, rare-metal pegmatites are abundant where one of the bounding subprovinces is characterized by a low- to high-grade metamorphic transition and contains abundant metasedimentary rocks and S-type peraluminous granites (Breaks et al. 1999). Areas within the Grenville Province in Ontario underlain by Archean rocks (Figure 28.1) fit this criteria, and thus may be prospective for rare-metal pegmatite fields, as follows. 1) abundant metasedimentary rocks occur near a low- to high-grade metamorphic transition (Temagami greenstone belt adjacent to the Pardo, Red Cedar Lake and Crerar gneisses), with the transition now roughly marked by the Grenville Front. 2) Pegmatites of Archean-age occur within the Grenville Province south of Temagami (e.g. Krogh and Davis 1970; Krogh 1994). 3) Plutonic rocks similar in chemical signature to the fertile, S-type Ghost Lake batholith in northwest Ontario (Breaks and Moore 1992) occur in several places near River Valley (Figure 28.2a). Archean S-type granitoids had not been previously noted in the Ontario Grenville Province. 4) The timing of plutonic and metamorphic events outlined in Table 28.1 is comparable to that found in other parts of the Superior Province containing rare-metal pegmatites (e.g., Easton 2000). Areas underlain by the Pardo and the Red Cedar Lake gneiss have the greatest potential for hosting rare-metal pegmatite fields.

East Bull Lake Intrusive Suite

RELATIONSHIP TO MURRAY FAULT SYSTEM

As shown in Figure 28.4a, the East Bull Lake, Agnew Lake, and May, Drury, Wisner and Falconbridge township bodies all occur north of the Murray fault system. The River Valley intrusion, the gabbroic anorthosite component of the Wanapitei Complex, the Red Deer Lake body, the Street Township body, and troctolitic and gabbroic anorthosite rocks of the Flett Township intrusion (also known as the Fall Lake anorthosite, Easton 1992) all lie south of the Murray fault system, even when accounting for the effects of Grenville orogenesis. If the Murray fault system is considered to mark the position of a subsequently re-activated rift boundary fault (e.g., Zolani et al. 1984), then this would have a bearing on mineral potential; that is, intrusions south of the fault would be closer to the area of active rifting, and thus may have formed from higher-volume magmatic systems. Higher magma volume can be a factor in increasing platinum-group element (PGE) content (e.g., Keays 1995). Alternatively, the Murray fault system may have developed post-emplacement of the East Bull Lake intrusive suite (but still largely prior to main Huronian Supergroup deposition). In this case, the Murray fault system would have no relevance with respect to PGE-Cu-Ni mineralization within the East Bull Lake intrusive suite.

TECTONIC CONTROLS ON EMPLACEMENT

As shown in Figure 28.4a, rocks of the East Bull Lake intrusive suite may be aligned in at least three different ways: 1) as a single, east-northeastly trending belt from Elliot Lake to the Ottawa River, 2) as a single belt offset by movement along the Upper Wanapitei River fault (~10 km of right-lateral movement, which is contrary to evidence for left-lateral movement along this fault (Buchan and Ernst 1994)), or 3) as two belts, some 15 to 25 km apart, with parts of the belts lying beneath the Huronian Supergroup. The western belt lies north of the Murray fault system and the eastern belt lies south of the Murray fault system. In this scenario, potential exists for undiscovered parts of the two belts of intrusions: i) beneath rocks of the Southern Province south of the Murray fault in the Massey area and ii) north of the Grenville Front in the Temagami area.

Regardless of which alignment is correct, it is not known if the distribution of the intrusions bears any relationship to original tectonic controls on emplacement, or is simply fortuitous, reflecting exhumation history. No major structural or geophysical discontinuity is present in conjunction with these intrusions, although it is possible that subsequent events have served to obscure any early structures. The location of the intrusions does not appear to bear any clear relationship to Huronian Supergroup stratigraphy (e.g., association with specific formations), nor are the intrusions always associated with thick accumulations of Huronian metavolcanic rocks, which might be expected given previous suggestions that the two were cogenetic (e.g., Card et al. 1972, 1984). The most consistent relationship is that the intrusions occur near contacts between Archean basement and rocks of the Huronian Supergroup. In the May Township and River Valley areas, however, these contacts are largely or wholly tectonic (Murray fault and Grenville Front, respectively). In the Drury, Wisner and Falconbridge township areas, contact relationships have been further modified by the Sudbury event, which also removed portions of the intrusions. Contact relationships between both the East Bull Lake and Agnew intrusions and the Huronian Supergroup are equivocal, and can be interpreted as wholly tectonic, or unconformable. Consequently, the significance of the relationship between the intrusions and contacts between Archean basement and Huronian strata cannot be evaluated fully.

DEPTH OF EMPLACEMENT

The depth of emplacement and the nature of the roof rocks of the East Bull Lake intrusive suite are not known for certain. The topic is significant for exploration, as emplacement at shallow depths means that it is likely major portions of the bodies have been removed through erosion, and consequently, petrochemical studies of the intrusion sample only part of the magmatic system. In contrast, emplacement at greater depths makes it more likely that the intrusions preserve complete stratigraphic sections, with subsequent implications for original magma composition, emplacement mechanism and magmatic differentiation (*see also* Hrominchuk, this volume).

The prevailing view, developed largely prior to reliable dating of the intrusions and the Huronian Supergroup, is that the East Bull Lake intrusive suite was emplaced at relatively high-crustal levels (<5 km), near the interface between Archean basement and the Huronian Supergroup. In this scenario, subsequent erosion has removed significant portions of the intrusions, so that all bodies possess incomplete stratigraphic sections. When examined critically, the evidence for high-level emplacement near the base of the Huronian Supergroup is circumstantial at best, as follows:

1. The East Bull Lake and River Valley intrusions are likely as much as 30 million years older than Huronian felsic volcanism (2475 to 2480 Ma *versus* 2445 to 2450 Ma). As the intrusions were emplaced before deposition of a significant portion of the Huronian Supergroup, then what were the cover rocks, and what happened to these cover rocks?

2. Unequivocal intrusive contacts with Huronian Supergroup rocks are poorly documented. The best example comes from the May Township intrusion; however, it has a chemical signature more closely linked with Huronian mafic volcanic rocks of the Salmay Lake Formation than with other East Bull Lake suite intrusions (Prevec 1993), thus the significance of this intrusive contact is equivocal, as it may not be representative of the entire suite. Also, Robertson (1976) noted that deformation and metamorphism in May Township obscures critical contact relations between the intrusive rocks and the Salmay Lake Formation. In contrast, Cape (1973) suggested that the upper part of the intrusion was eroded prior to

deposition of the Salmay Lake Formation. Reports of conglomerates containing gabbroic clasts possible derived from the Drury township body (Dressler 1984) only indicate that the intrusions were emplaced, and exposed, prior to Huronian sedimentation.

At River Valley and in Street Township, the River Valley intrusion appears to be emplaced at the interface between a domain of migmatized supracrustal rocks and a domain of granitoid plutonic rocks. Huronian Supergroup rocks are only observed in tectonic contact with the River Valley intrusion along the Grenville Front (Easton and Hrominchuk 1999). For the East Bull and Agnew Lake intrusions, the same suggestion could be made, especially for the former, as it occurs near the interface between the Whiskey Lake greenstone belt and a granitoid-dominated domain (Figure 28.4a). The Wisner township body was likely emplaced near the contact between the Cartier granite and the Levack gneiss complex.

It is therefore equally possible that the East Bull Lake intrusive suite was emplaced wholly into Archean rocks along major lithological boundaries. Depth of emplacement could range from relatively high in the crust (3 to 5 km for greenstone-granite interface) to mid-crustal levels (10 km for migmatite-granitoid interface), as shown in Figure 28.3. A consequence of deeper level emplacement is that both the basal and roof contacts of the intrusion might be preserved. Parts of the River Valley intrusion in Henry and Loughrin townships may be the best area to explore for such contacts. Note that even if the intrusions were emplaced solely into Archean crust, exhumation between 2640 and 2475 Ma, means that emplacement could have occurred at high levels in the crust (2 to 5 km), thereby allowing locally for erosion and exposure prior to main Huronian Supergroup deposition. Ongoing work by Hrominchuk (this volume) may further constrain emplacement depth and original thickness of the River Valley intrusion.

An unknown factor is the effect of tectonic unroofing and transport of these intrusions due to thrusting during the Penokean orogeny (defined broadly, herein, as 1850-1700 Ma). Penokean thrusting may be an important process in juxtaposing these intrusions against Huronian Supergroup rocks in the Elliot Lake area, and may have been a significant factor in allowing for uplift and exposure of the River Valley intrusion during the Grenville orogeny.

ACKNOWLEDGMENTS

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29. Project Unit 99-019. Geology, Stratigraphy, Geochemistry, and Copper-Nickel-Platinum Group Element Mineralization in the River Valley Intrusion

J.L. Hrominchuk[1]

[1]Mineral Exploration Research Centre, Laurentian University

INTRODUCTION

Since the summer of 1998, the River Valley intrusion has been the subject of ongoing Cu-Ni-PGE mineral exploration. Because of this interest, a Laurentian University–Ontario Geological Survey partnership project focusing on the intrusion north of the Sturgeon River was begun in May 1999. First-year progress was reported in Hrominchuk (1999). Second-year field work was conducted by the author from mid-May to early September 2000 in Dana and Crerar townships north of the Sturgeon River (Figure 29.1). The information in this paper will be expanded upon in a M.Sc. thesis at Laurentian University by the author.

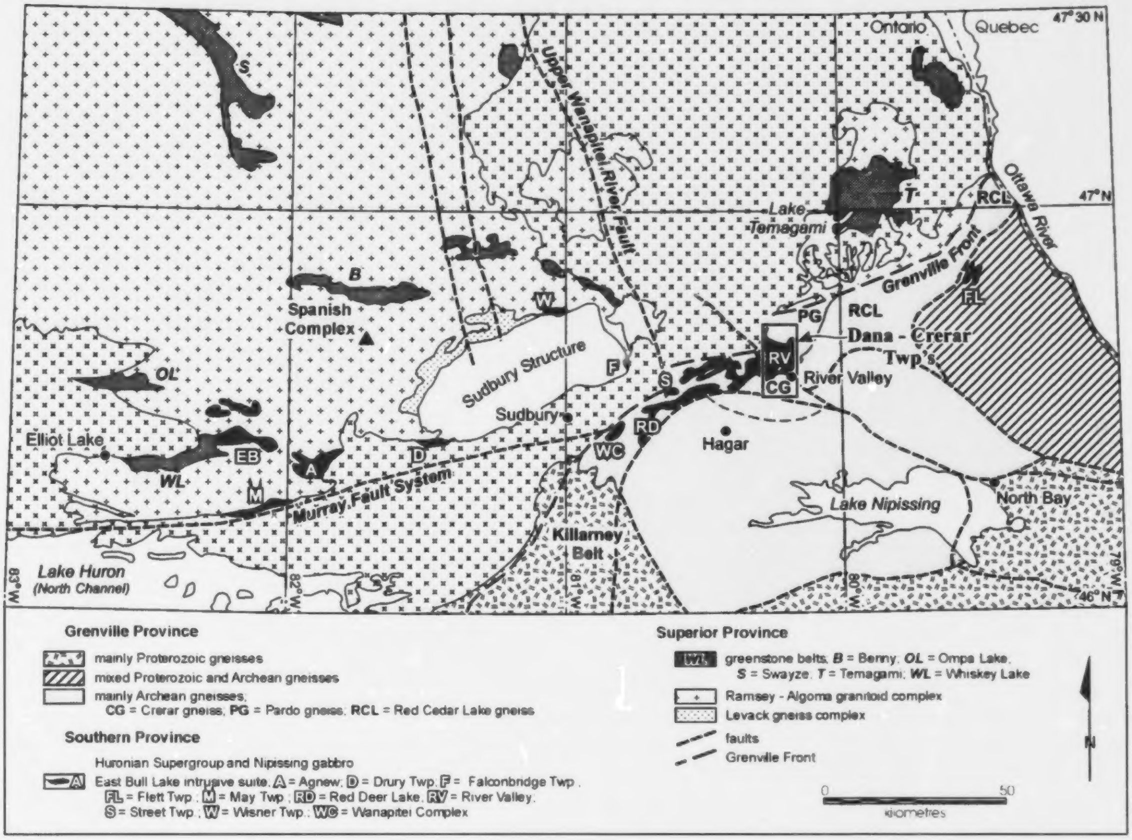
GEOLOGY OF THE RIVER VALLEY INTRUSION

The River Valley intrusion is a Paleoproterozoic intrusion of gabbronoritic and related rocks, roughly 100 km^2 in size, located roughly 50 km northeast of Sudbury (Figure 29.1). The River Valley intrusion has been dated at $2475^{+2}/_{-1}$ Ma (L.M. Heaman, geochronologist, personal communication, 1999), which is the same age as the East Bull Lake intrusion and other East Bull Lake intrusive suite (EBLI) bodies adjacent to, and west of, the Sudbury Igneous Complex. The EBLI bodies occur at the boundary between the Archean Superior Province and the Paleoproterozoic Southern Province, and are associated with rifting of the Superior Province at 2440 Ma to 2490 Ma (e.g., Vogel et al. 1998). The River Valley intrusion intruded granitic plutonic rocks (alkali feldspar granite and syenite), and regionally folded migmatitic gneisses, but lies in fault contact with Huronian Supergroup metavolcanic and metasedimentary rocks. The River Valley intrusion has been variably affected by the Grenville Orogeny, and lies within the Grenville Province, mainly within the Grenville Front tectonic zone. In Dana and Crerar townships, the Grenville Front is a wide zone of anastomosing deformation zones and imbricate thrust faults, rather than a single fault (e.g., Davidson 1986; Easton and Hrominchuk 1999).

The River Valley intrusion is characterized by conspicuous purple to black plagioclase, with the colour due to the presence of abundant fine inclusions of Fe-Ti oxide (Ashwal and Wooden 1989) and hercynian spinel. Plagioclase (An_{55-80}), orthopyroxene (En_{60-80}) and olivine (Fo_{70-75}) are common in well-preserved samples. Other primary igneous minerals are inverted pigeonite, augite, and accessory Fe-Ti oxides and calcic myrmekite. Common metamorphic minerals are amphibole, biotite, garnet, light-coloured (recrystallized) plagioclase with accessory quartz, epidote, sericite, chlorite, serpentine and carbonate.

Metamorphism and Deformation

The River Valley intrusion north of the Sturgeon River is variably metamorphosed, ranging from relatively unmetamorphosed to upper amphibolite facies or higher. Mylonitic, gneissic and schistose equivalents of gabbronoritic and other River Valley intrusion rocks occur throughout the study area. Within the study area, the intrusion is cut by numerous thrust faults in addition to being offset by strike-slip and dip-slip faults. Structural analysis suggests that the main direction of thrusting was toward the present northeast. These major deformation and fault zones are marked by linear topographic features (e.g., swamps, river courses). Primary igneous textures are preserved in "core areas" generally located 1) away from and topographically above major deformation zones, and 2) structurally above but proximal to thrust fault zones. Typically, primary igneous mineralogy is preserved within these "core areas" representing original cumulate mineralogy. The development of coronas around olivine and orthopyroxene grains, as well as the localized presence of garnet, biotite and amphibole, indicate that even the more pristine "core areas" underwent some metamorphic reaction. Cox and Indares (1999) suggested that in coarse-grained, dry, igneous bodies, metamorphic reactions are slow, resulting in corona formation and allowing for the preservation of igneous relicts. Nearer the margins of the body, in



Ontario
Quebec
47°30 N
47°N
S
Upper Wanapitei River Fault
T
Lake Temagami
RCL
Ottawa River
Grenville Front
B
Spanish Complex
W
FL
PG
RCL
Dana - Crerar Twp's
RV
CG
River Valley
Sudbury Structure
F
S
OL
Sudbury
RD
Hagar
Elliot Lake
EB
WC
A
D
WL
M
Murray Fault System
Lake Nipissing
North Bay
Killarney Belt
Lake Huron
(North Channel)
83°W
82°W
81°W
80°W
79°W
46°N
Grenville Province
mainly Proterozoic gneisses
mixed Proterozoic and Archean gneisses
mainly Archean gneisses;
CG = Crerar gneiss; PG = Pardo gneiss; RCL = Red Cedar Lake gneiss
Southern Province
Huronian Supergroup and Nipissing gabbro
East Bull Lake intrusive suite. A = Agnew; D = Drury Twp; F = Falconbridge Twp.
FL = Flett Twp.; M = May Twp.; RD = Red Deer Lake; RV = River Valley;
S = Street Twp.; W = Wisner Twp.; WC = Wanapitei Complex
Superior Province
WL
greenstone belts. B = Benny; OL = Ompa Lake,
S = Swayze; T = Temagami; WL = Whiskey Lake
Ramsey - Algoma granitoid complex
Levack gneiss complex
faults
Grenville Front
N
0
50
kilometres

Figure 29.1. Location map showing distribution of Archean and Proterozoic rocks in the south-central Canadian shield in Ontario, as well as the distribution of rocks of the East Bull Lake intrusive suite. Proterozoic intrusive rocks within the Grenville Province have been omitted for clarity.

deformed and hydrated rocks, metamorphic reactions would go to completion, and the rocks would be more susceptible to retrograde metamorphism. On the other hand, Joesten (1986) suggested that slow cooling of a mafic magma at high pressures can explain corona texture, clouded plagioclase and the preservation of coarse-grained igneous textures. Joesten (1986) cited the composition of corona phases, the thermodynamic instability of the reactions in most corona assemblages, the presence of clouded plagioclase in rocks with no olivine, and the widespread preservation of igneous textures in troctolites and gabbros as evidence of a magmatic origin for some corona structures. Although either of the above processes is viable, the evidence to date from the River Valley intrusion favours a metamorphic origin for the corona textures, with spectacular preservation of igneous texture.

Stratigraphy

An interpretive stratigraphic section for the River Valley intrusion is presented in Figure 29.2, and is a refinement of a preliminary section presented in Hrominchuk (1999). Five units or zones are recognized (Figure 29.2): 1) a Marginal Zone, 2) an Inclusion/Fragment-bearing Zone, 3) a Layered Olivine Gabbronorite Zone, 4) a Layered Gabbronorite Zone, and 5) a vari-textured to massive Leucogabbronorite Zone.

The Marginal Zone is characterized by a fine- to medium-grained, black plagioclase phyric, quartz-eye-bearing gabbronorite that is partly chilled and typically is strongly mineralized at the contact with granitic plutonic and gneissic rocks. Where the River Valley intrusion is in contact with gneissic rocks, the Marginal Zone becomes a complex chaotic mixture of footwall blocks and fine- to medium-grained gabbronoritic rocks. Because rocks immediately adjacent to the contact usually contain large blocks and screens of footwall material, exact definition of the contact in some areas is problematic.

The Inclusion/Fragment-Bearing Zone is gradational with the Marginal Zone below, but its appearance is marked by a sharp increase in the size and amount of felsic fragments and the appearance of compositionally and texturally varied mafic to ultramafic inclusions or xenoliths. The host rocks to these fragments, inclusions, or xenoliths are similar to those of the underlying marginal rocks but are generally more gabbroic and contain finely disseminated sulphides. Felsic fragments are rounded to sub-angular, ranging in size from a few millimetres to a metre in scale, but most are 2 to 15 cm in size, and consist mostly of quartz with varied amounts of alkali feldspar. Felsic fragments are commonly surrounded by a very coarse-grained to pegmatitic growth of pyroxenite and melanogabbronorite. Inclusions are abundant, and locally (e.g., outcrop scale) may constitute up to 100% of the rock. Most inclusions are olivine-bearing gabbronorite to peridotite in composition, with subordinate leucogabbronorite. Inclusions are usually well rounded and weakly to very strongly mineralized.

The Olivine Gabbronorite Zone is composed of 0.3 to 1.5 m thick layers that are olivine-rich at the base, and erosive into underlying layers, and which grade upward into olivine gabbronorite or troctolite to slightly more plagioclase-rich end members. Layers are deeply weathered due to the presence of serpentine and fine-grained magnetite after olivine. This zone is well exposed in only a few places, but is normally 50 to 150 m thick, and seems to grade into the overlying, olivine-poor Layered Gabbronorite Zone.

The Layered Gabbronorite Zone is composed of metre-scale modally layered rocks that reach a maximum continuous thickness of roughly 200 m. This represents a minimum stratigraphic thickness, as the top of the section is always cut by faults and zones of intense deformation. This unit consists of generally 1 m thick layers of norite to gabbronorite (±olivine) overlain by 1 m thick leucogabbronorite layers. Locally, this unit is very coarse grained, with zones rich in felsic fragments and surrounded by pegmatite pods containing epidote, magnetite, alkali feldspar, plagioclase, amphibole, pyroxene, biotite and garnet. No significant mineralization was found in this zone.

The Massive Leucogabbronorite Zone is a generally unlayered, massive leucogabbronorite to anorthosite found at the highest stratigraphic levels of the intrusion (generally in the upper parts of topographic highs) in Dana Township. A complete section of these rocks has not yet been found in Dana Township and they are commonly highly deformed or faulted. Deformed equivalents of these rocks may preserve a more complete section in Crerar Township (Easton and Hrominchuk 1999).

Mineralogy

The mineralogy of the intrusion is complicated by regional metamorphism to upper amphibolite facies and intense deformation; nonetheless, primary igneous mineralogy is present, and is described for each stratigraphic unit along with the typical metamorphic and alteration mineralogy of each.

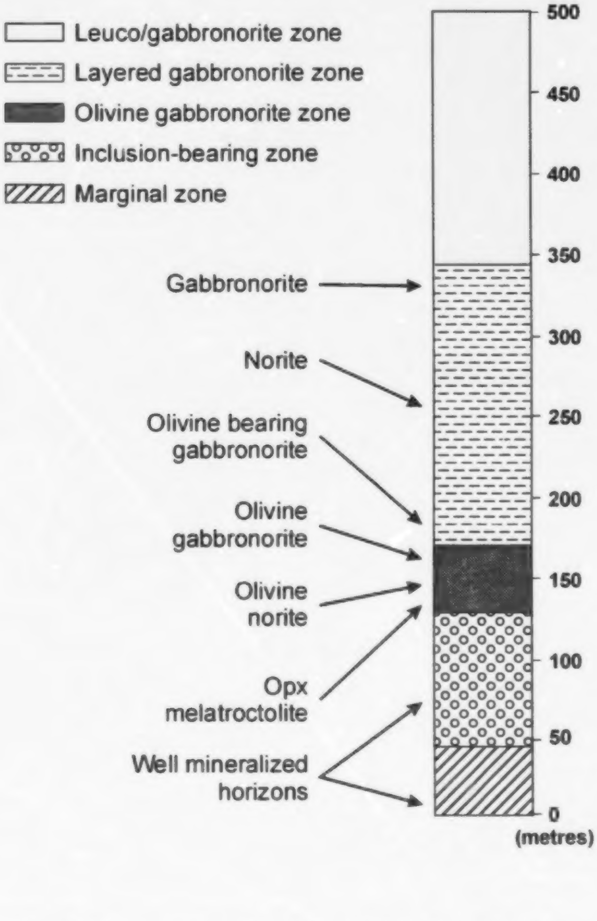


Figure 29.2. Stratigraphy of the River Valley intrusion, based on measured sections and structural and geological interpretation. This section supercedes the preliminary section presented in Hrominchuk (1999).

The Marginal Zone consists mostly of medium-grained norite to gabbronorite and is normally well preserved (Figure 29.3a). In thin section, the rock consists of dark-brown to tan-coloured cumulate (An_{79} core and An_{74} rim) to intercumulate (An_{68}) plagioclase, woody-brown cumulate orthopyroxene, interstitial clinopyroxene, ±olivine, with accessory magnetite, quartz, biotite, sulphides and calcic myrmekite. Granitic fragments are rarely visible in thin section. Where metamorphosed, this rock usually contains fine-grained acicular amphibole (actinolite); plagioclase is white to clear and can begin to develop zoisite alteration minerals. Other metamorphic phases include garnet, hornblende and biotite.

The Inclusion/Fragment-Bearing Zone is extremely varied in mineralogy and texture; the host matrix to the inclusions and fragments is very similar to the underlying Marginal Zone (Figure 29.3c) but with more olivine, varied sulphide content and a slightly coarser average grain size (medium-grained). Inclusions are of three main types: alkali feldspar granite and other granitic rocks, amphibolite and olivine-rich rocks (troctolites, peridotites). Granitic rock fragments contain potassium-feldspar, alkali feldspar, quartz, biotite and amphibole, are fine to coarse grained, and have a bleached appearance. Amphibolite fragments are generally actinolite and tremolite with epidote, clinozoisite and quartz, with a fine-grained massive to radial texture. Troctolite or peridotite inclusions are similar in all respects to the olivine norite to mela-troctolite/peridotite from the Olivine Gabbronorite Zone (Figure 29.3b) described below; when metamorphosed these inclusions become rich in biotite, actinolite, hornblende and garnet.

The Olivine Gabbronorite Zone consists of a wide range of rocks; however, olivine is present in most, with troctolite and olivine norite predominant. Olivine is generally medium to coarse grained, magnesium-rich (Fo_{74}) coronitic, and variably serpentinized (Figure 29.3d, 29.3e). Plagioclase is calcic (An_{70-75}), dark coloured, and inclusion rich. Orthopyroxene occurs in two forms, as euhedral woody prisms, and as large (up to 10 cm) oikocrysts enclosing olivine and plagioclase. Clinopyroxene is found only as interstitial anhedral crystals.

The Layered Gabbronorite Zone consists of layers that begin as olivine-bearing norite and fractionates to gabbro. Coarse-grained black norite dominates the unit (Figure 29.3f). It consists of large (2 cm) orthopyroxene, brown plagioclase (up to 3 cm), interstitial clinopyroxene and inverted pigeonite, and rare olivine. Metamorphosed equivalents contain altered plagioclase, amphiboles (both fine-grained actinolite and coarse-grained hornblende), small (pyrope- grossular- almandine) garnets and quartz.

Rocks above the Layered Gabbronorite Zone are mainly leucogabbro to gabbroic anorthosite with rare anorthosite. These more fractionated rocks consist dominantly of dark plagioclase with subordinate interstitial and primocryst clinopyroxene and inverted pigeonite. When metamorphosed, the more leucocratic rocks tend to form very white-weathering rocks with small pods or blobs of amphibole-rich material dispersed throughout.

Geochemistry

Whole rock geochemistry indicates that all rocks of the River Valley intrusion formed from a single parent magma of high-magnesium, high-aluminum, low-titanium tholeiitic character similar to that documented for the other EBLI intrusions (e.g., Vogel et al. 1999). Representative analysis for each Olivine Gabbronorite Zone rocks are olivine-normative, whereas the bulk of the rocks in the upper units are only silica-saturated. Samples from the Marginal Zone (samples CZ7-500, CZ7-1000, Table 29.1) stratigraphic unit are presented in Table 29.1. Rocks of the Marginal Zone are quartz normative (CIPW), show much higher Ti, Fe, K, Na, P, Ba, Zr and Y contents than do most other River Valley intrusion samples (e.g., analyses 3 to 10, Table 29.1). These elemental variations are interpreted as a possible contamination signature; rare earth element (REE) analysis are being conducted in order to assess the extent and significance of this contamination. Although Ti and Fe might not normally be considered indicative of wall rock contamination, the high concentration of these elements in some footwall phases (e.g., analysis 12, Table 29.1) relative to typical River Valley intrusive rocks (analyses 3 to 10, Table 29.1) is consistent with some of the observed Ti and Fe content in analyses 1 and 2 resulting from wall rock assimilation.

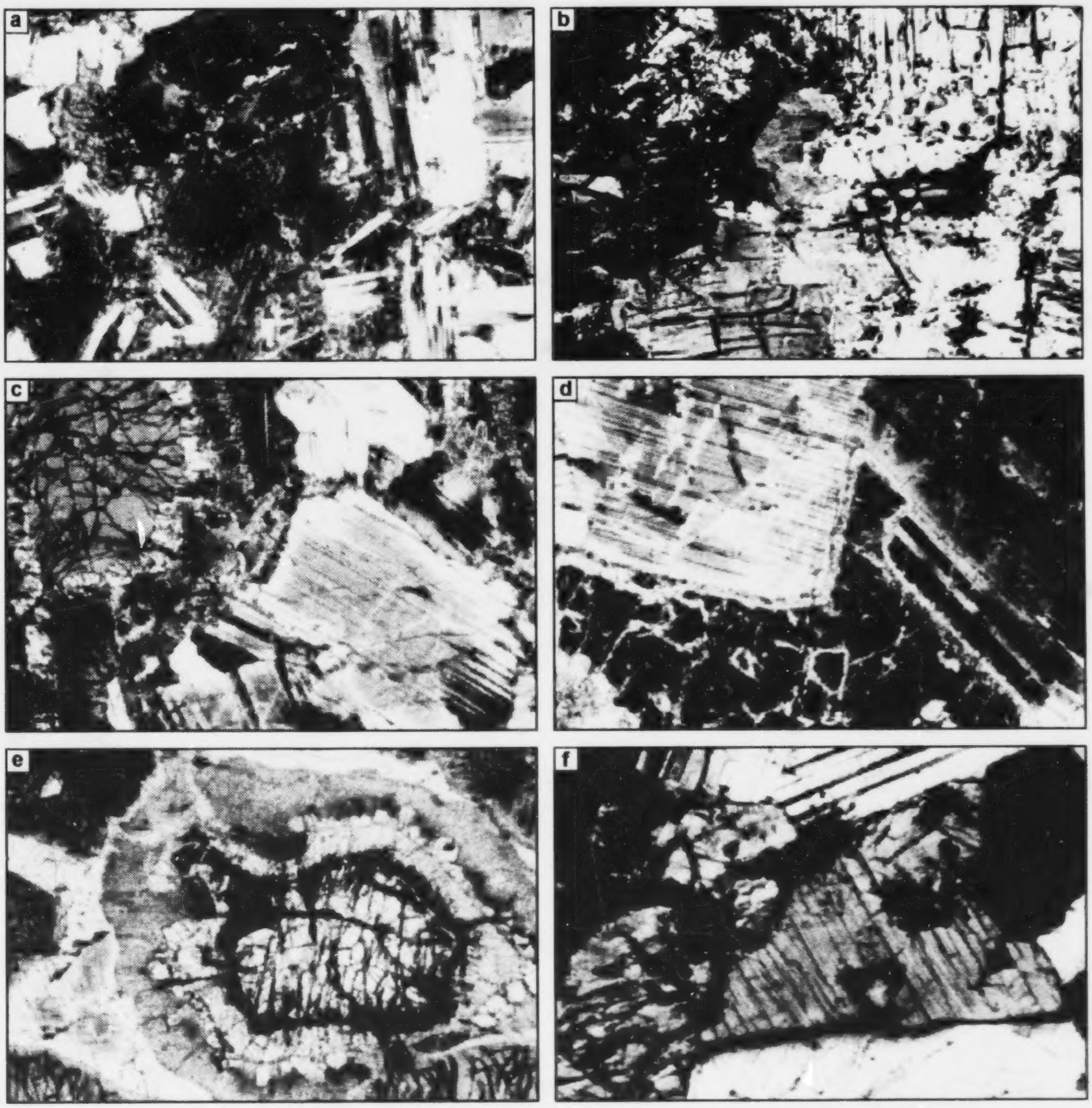


Figure 29.3. Photomicrographs of representative rocks from the River Valley intrusion. **A)** Sample H170, Marginal Zone diabasic gabbronorite, field of view = 4.5 x 3 mm. **B)** Sample H243, medium-grained clinopyroxene-troctolite inclusion from the Inclusion/Fragment-Bearing Zone, field of view = 1 x 1.5 mm. **C)** Sample H243, medium-grained olivine-bearing gabbronorite representing matrix to inclusion-bearing rocks, Inclusion/Fragment-Bearing Zone, field of view = 1 x 1.5 mm. **D)** Sample H371A, coronitic tractolite to mela-troctolite from the Olivine Gabbronorite Zone, field of view = 4.5 x 3 mm. **E)** Sample H343, coronitic olivine norite from the Olivine Gabbronorite Zone, field of view = 4.5 x 3 mm. **F)** Sample H159, coarse-grained orthopyroxene oikocrystic norite from the Layered Gabbronorite Zone, field of view = 4.5 x 3 mm.

The matrix of the Inclusion/Fragment-Bearing Zone (sample H243, Table 29.1) is high in Mg, Ca, Al and Fe, consistent with its plagioclase, orthopyroxene and olivine-dominated mineralogy. Disseminated sulphides in this matrix are dominantly chalcopyrite and pyrrhotite up to ~ 1%, and with Pt+Pd+Au up to 0.5g/t (Cu/Ni ratios ~ 2; Pt/Pd ratios ~ 0.4, Pt+Pd+Au up to 0.5g/t.) The inclusions, fragments and xenoliths of this zone are extremely varied in composition, partially resorbed, and commonly mineralized; felsic fragments show similarities to the footwall alkali feldspar granite. Mafic inclusions (sample H242, Table 29.1) are very similar to the rocks in the lowest portion of the Layered Olivine Gabbronorite Zone. The Olivine Gabbronorite Zone is characterized by rocks high in MgO (15 to 24 wt.%) and low in SiO_2 (38 to 45 wt.%), with anomalous Ni contents attributed to the predominance of primocryst olivine in this zone (samples H269, JLH S1-S3, Table 29.1). Rocks from the Layered Gabbronorite Zone show gradual fractionation to more silicon-, aluminum-, calcium-, sodium-, potassium-rich and more magnesium-poor compositions (samples JLH S2-S1, JLH S2-S4, Table 29.1), a trend also observed in the uppermost stratigraphic unit (samples H116, H244, Table 29.1).

COMPARISONS WITH THE EAST BULL LAKE INTRUSIVE SUITE

The River Valley intrusion has been correlated with the East Bull Lake intrusive suite (EBLI) on the basis of age, composition and setting (e.g., Hrominchuk 1999). Considerable work has been done on the EBLI suite, including geology, geochemistry and intrusive setting (e.g., James and Born 1985; McCrank et al. 1989; Vogel et al. 1998) and geology and mineralization (Peck et al. 1993, 1995). Although grossly similar, there are some major apparent differences between the River Valley intrusion and the other EBLI bodies, as follows: 1) the River Valley intrusion likely represents a much larger original intrusive body than either the Agnew Lake or East Bull Lake intrusion. 2) the River Valley intrusion lies only in fault contact with rocks of the Southern Province, whereas the Agnew Lake and East Bull Lake intrusions are in apparent unconformable contact with sedimentary rocks of the Southern Province (*see* discussion by Easton, this volume). 3) Preservation of primary igneous mineralogy and textures is much more complete in the River Valley intrusion than is known in the other EBLI intrusions to the west. 4) There is more evidence for a highly dynamic magma system in the River Valley intrusion (e.g., fragments, interaction with marginal rocks, inclusions, erosive-graded layering, mass contamination of contact magmatic rocks) than is indicated in the other intrusions. 5) The stratigraphy of the River Valley intrusion indicates a much more mafic system with less differentiation from olivine melanorite to leucogabbronorite, unlike the East Bull and Agnew Lake intrusions where olivine gabbronorite eventually fractionates to ferrosyenite (e.g., Vogel et al. 1999). These differences may have significant implications with respect to depth of emplacement, parent magma composition, magma dynamics and PGE-Cu-Ni mineralization for the entire intrusive suite, topics that will be more fully addressed in the author's M.Sc. thesis (*see* also Easton, this volume). For example, is the EBLI suite one large discontinuous sill formed from intrusion and differentiation of essentially one magma body, or does it represent smaller separate intrusions emplaced at different depths, by a continuously fractionating magmatic system?

PGE-CU-NI MINERALIZATION IN THE RIVER VALLEY INTRUSION

To date, PGE-Cu-Ni mineralization within the EBLI suite has been found near the basal contacts of the various intrusions, and no comprehensive model yet exists that explains the processes involved in producing this contact-style of mineralization. The River Valley intrusion is no exception, and highly anomalous (>10g/t) PGE values and massive to near massive Cu-Ni mineralization are found adjacent and proximal to primary igneous contacts of the intrusion. Contact zone mineralization occurs as disseminated to blebby sulphide (cpy + po) in rocks that lie at (above or within) the intrusion's interface

Table 29.1. Representative chemical analyses from the River Valley intrusion and country rocks. Numbers in bold reflect elements indicative of contamination in River Valley intrusive rocks (*see* text for discussion).

Number	1	2	3	4	5	6	7	8	9	10
Sample No.	CZ7-500	CZ7-1000	H242	H243	H371A	JLHS1-S3	JLHS2-S1	JLHS2-S4	H116	H244
Zone	MZ	MZ	IFBZ	IFBZ	OLGN	OLGN	GN	GN	LGN	LGN
Rock Type	f.g. gabbro-diabase	f.g. gabbro-diabase	c.g. troctolite inclusion	m.g. olivine gabbronorite	c.g. troctolite	c.g. mela-troctolite	c.g. gabbro–norite	c.g. norite	c.g. gabbronoritic anorthosite	c.g. gabbronoritic anorthosite
Easting	558420	558420	559139	559138	559586	559646	558632	558633	556335	558511
Northing	5167880	5168380	5167454	5167453	5166117	5166117	5165021	5165169	5166587	5165205
wt. %										
SiO_2	**52.51**	**51.85**	44.14	48.42	43.32	38.30	50.21	50.81	49.59	51.07
TiO_2	**0.93**	**0.91**	0.16	0.21	0.10	0.14	0.13	0.18	0.16	0.10
Al_2O_3	14.17	14.36	12.79	18.81	18.30	7.85	19.95	18.43	25.52	22.84
Fe_2O_3	13.40	13.09	2.57	1.51	9.34	15.10	8.23	8.92	1.99	1.08
FeO	N/A	N/A	13.21	8.38	N/A	N/A	N/A	N/A	2.55	4.47
MnO	0.17	0.18	0.20	0.14	0.12	0.20	0.13	0.14	0.07	0.11
MgO	5.16	5.48	15.67	10.16	14.06	23.72	6.90	7.46	3.17	5.38
CaO	8.79	8.96	7.18	9.82	8.37	3.70	10.32	11.19	13.65	10.91
Na_2O	**2.16**	**2.25**	1.18	1.87	1.34	0.70	2.09	1.87	2.41	3.03
K_2O	**0.85**	**0.94**	0.20	0.30	0.28	0.12	0.21	0.20	0.30	0.22
P_2O_5	**0.09**	**0.10**	0.01	0.03	0.03	0.04	0.03	0.03	0.01	0.01
CO_2	0.26	0.22	<0.03	0.07	0.22	0.22	0.18	0.15	0.03	0.08
S	0.024	<0.005	0.67	0.18	<0.005	<0.005	<0.005	<0.005	<0.01	<0.01
LOI	1.36	1.60	0.01	0.25	4.51	10.12	1.99	0.43	0.98	0.72
Total	99.59	99.72	97.32	99.90	99.77	99.99	100.19	99.66	100.40	99.94
Mg #	40.9	43.0	62.1	62.9	73.0	73.9	60.2	60.1	54.2	61.6
ppm										
Cr	90	115	203	250	136	159	73	90	138	86
Ni	57	75	1840	623	595	1360	97	92	44	83
Co	50	39	119	65	78	155	41	38	13	28
Sc	29	30	15	14	11	17	20	28	13	11
V	284	287	93	91	43	48	71	109	75	55
Cu	171	401	4512	1320	16	162	18	94	46	18
Zn	109	108	122	84	92	111	56	66	36	51
Rb	37	46	3	5	4	1	16	10	4	3
Ba	**341**	**251**	81	110	93	79	139	121	85	89
Sr	255	193	151	219	235	94	238	220	258	246
Nb	**2.9**	**0.9**	0.4	0.7	0.3	0.9	0.2	0.2	0.4	0.1
Zr	**86**	**80**	12	21	7	17	3	4	9	3
Y	**16**	**18**	4	6	4	8	0.7	2	5	2
Zr/Y	5.5	4.3	3.0	3.5	1.7	2.2	4.7	2.4	1.8	1.5
ppb										
Au			145	59					5	<5
Pt			576	106					15	<8
Pd			1980	293					19	<8
Pt/Pd			0.30	0.36					0.79	
Au+Pt+Pd			2701	458					39	<21

Samples 1, 2, 5, 6, 7, 8 analyzed by the Mineral Exploration Research Centre, Laurentian University. Samples 3, 4, 9, 10, 11, 12, 13, 14, 15 analyzed by the Geoscience Laboratories, Ontario Ministry of Northern Development and Mines. Samples 3, 4, 9, 10, 11, 14, 15 were previously reported in Easton and Hrominchuk (1999). Abbreviations: c.g. = coarse-grained, f.g. = fine-grained; N/A = not analyzed; IFBZ = Inclusion/Fragment-Bearing Zone, GN = Gabbronorite Zone, LGN = Leucogabbronorite Zone, MZ = Marginal Zone, OLGN = Olivine Gabbronorite Zone. Easting and northings are in UTM zone 17, NAD 27 datum.

Table 29.1. continued.

Number	11	12	13	14	15
Sample No.	H2139	99RME-0375	99RME-0025	99RME-0031	99RME-0137
Zone	Footwall	Footwall	Footwall	Dike	Dike
Rock Type	Alkali-feldspar granite	biotite diorite gneiss	Migmatitic metwacke (Pardo gneiss)	Matachewan diabase dike	Sudbury diabase dike
Easting	559773	558770	560005	559903	561245
Northing	5167006	5159210	5173855	5174205	5169035
wt. %					
SiO_2	72.26	55.29	63.76	50.36	45.50
TiO_2	0.10	1.57	0.58	1.15	2.97
Al_2O_3	15.21	13.8	15.62	14.07	15.60
Fe_2O_3	0.16	3.37	2.09	3.09	2.16
FeO	0.44	10.02	3.11	11.11	13.60
MnO	0.01	0.17	0.06	0.22	0.23
MgO	0.28	3.35	3.08	5.89	5.21
CaO	1.14	6.73	3.23	10.02	8.21
Na_2O	4.02	2.58	3.63	1.97	3.26
K_2O	5.52	1.94	2.97	0.68	1.45
P_2O_5	0.03	0.19	0.13	0.12	0.75
CO_2	0.20	0.11	0.12	<0.03	0.12
S	<0.01	0.04	0.09	0.12	0.12
LOI	0.61	0.76	1.18	0.68	0.09
Total	99.78	99.77	99.44	99.36	99.03
Mg #	46.1	31.4	52.4	43.0	37.4
ppm					
Cr	20	30	183	90	37
Ni	<5	57	64	81	68
Co	<5	41	19	57	57
Sc	<1	26	9	37	26
V	11	330	17	319	204
Cu	<5	92	10	278	71
Zn	15	142	94	67	190
Rb	106	75	139	13	41
Ba	1748	593	670	91	673
Sr	950	157	464	145	250
Nb	1.2	12.5	6.8	4.8	21.6
Zr	93	166	117	92	348
Y	1	47	8	31	59
Zr/Y	93	3.5	14.6	3.0	5.9
ppb					
Au	<5	9	<5	7	<5
Pt	<8	6	<8	38	<8
Pd	<8	14	<8	72	<8
Pt/Pd		0.43		0.53	
Au+Pt+Pd	<21	29	<21	117	<21

with the footwall. This zone is highly chaotic; footwall blocks and screens, mafic and felsic dykes, and vari-textured, varied-composition gabbronoritic rocks complicate the understanding of the exact host and source of the sulphides and the PGEs. The contact zone and its mineralization appears to be more chaotic where the body intrudes gneissic rocks, rather than syenitic or granitic rocks. Both types of contact, though, seem to contain highly anomalous PGE values.

Areas of highly anomalous PGE-Cu-Ni mineralization also occur in the Inclusion/Fragment-Bearing Zone. Disseminated to semi-massive to massive sulphides appear to be somewhat erratically distributed in the zone, with the more disseminated mineralization occurring in the host rock, and the more massive sulphides occurring in and around the inclusions. Mineralization occurs in the irregular pods or layers that contain felsic fragments and the mafic to ultramafic inclusions or xenoliths of varied size, texture and composition. These fragments/inclusions are hosted by a fine- to medium-grained quartz-eye-bearing gabbronorite, which may contain disseminated sulphides.

Whether within the Marginal Zone or in the overlying Inclusion/Fragment-Bearing Zone, PGE-Cu-Ni mineralization in the River Valley intrusion appears to be directly related to contamination of a fresh sulphur-undersaturated, platinum group element-rich magma by footwall fragments and cognate xenoliths. Contamination of the magma serves to drive it to S saturation; once that is accomplished, magma turbulence can concentrate PGE into the very small amount of sulphide present (e.g., Lesher et al. 1999; Lambert et al. 1998). Thus, significant mineralization should be found in areas of extreme magma dynamics, consistent with intense brecciation, contamination and a high R-factor. Generally, where evidence for contamination is absent or minimal, (i.e., low dynamics and/or no fragments) mineralization is absent to minimal. Where evidence for contamination is high, (as indicated in the River Valley intrusion by small resorbed fragments, blue quartz eyes, and elevated Ti, K, Na, Zr, Y) mineralization is good (assuming that the magma had a sufficiently high background level of PGE). Therefore, where fresh, platinum group element-rich magma reaches sulphide saturation through contamination, fractionation or other processes, and has sufficient R-factor (dynamic and turbulent magma), good grades of PGE mineralization should result. These criteria are most prevalent in the River Valley intrusion in rocks of the Marginal and Inclusion/Fragment-Bearing zones.

RECOMMENDATIONS FOR EXPLORATION

In light of what has been learned about the mineralization within the River Valley intrusion over the last two summers, and from the other EBLI intrusions, the following approaches to PGE exploration may yield significant results.

- Detailed geological mapping, concentrating on rocks located at or near areas where an igneous contact is known or inferred.
- Focus on rocks that show evidence of contamination (e.g., fragment-bearing, quartz-eye-bearing), and those areas containing rocks with a contaminated geochemical signature.
- Mapping and sampling of heterogeneous gabbronoritic rocks of the Inclusion/Fragment-Bearing Zone. These may occur some hundreds of metres or more from the contact of the intrusion.
- Sampling of, and determination of PGE concentration, in intrusion rocks without visible sulphides or oxides, as many samples that are highly anomalous in PGE are largely devoid of sulphide.
- The use of geophysical surveys to: 1) identify contacts in areas where exposure is poor and to determine intrusion thickness near to the footwall (e.g., magnetic, gravity surveys), and 2) outline mineralization in areas of high mineral potential (e.g., induced-polarization surveys).
- Utilization of surficial sediment techniques (Tardif 2000) in areas of poor exposure or for regional exploration in drift covered areas.

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J.G. Spray, M. Boast, A.J. Murphy, J.P. O'Connor, R.G. Scott and M. Tuchscherer

Planetary and Space Science Centre, Department of Geology, University of New Brunswick, Fredericton, NB

INTRODUCTION

This year marks a decade of activity in the Sudbury region by University of New Brunswick geologists. The 2000 field season saw three graduate students with three field assistants working in the North Range of the Sudbury Structure. This included projects on the Foy and Whistle–Parkin Offset Dikes and on the metamorphic aureole to the Sudbury Igneous Complex. The Impact Geology Group's primary focus is the study of impact craters and related shock processes. Most of the group members are working on the Sudbury Structure; one of the world's largest and best exposed impact structures. This year also saw the opening of the Planetary and Space Science Centre at the University of New Brunswick — a facility dedicated to the study of planetary geology. The current aim of the Sudbury program is to establish the geological setting and origin of the radial and concentric fracture-fault systems located around the main mass of the Sudbury Igneous Complex. Many of the fracture-faults house dike and/or breccia systems that have been mined for their Cu-Ni-PGE deposits over the last century (e.g., Whistle, Copper Cliff, Foy, Worthington, Frood–Stobie). Understanding the impact tectonics of the structure will, therefore, reveal how the fracture-fault systems formed and evolved. Consideration is also being given to the metamorphic history of the Sudbury region, with particular reference to distinguishing pre- and post-impact tectonothermal events (Thompson et al., 1998). This year, investigations of metamorphism include studies of the aureole around the Sudbury Igneous Complex.

FOY OFFSET DIKE

The Foy Offset Dike is a quartz diorite-bearing radial intrusion that extends into the footwall from the north rim of the Sudbury Igneous Complex in Bowell Township for more than 35 km north-northwest into Sweeny Township (Figure 30.1). It is the longest of the known radial offset dikes. The proximal Foy (i.e., between the Sudbury Igneous Complex and the Hess Offset) intersects and terminates at the Hess concentric offset in Tyrone Township (Wood, 1998; Wood and Spray, 1998). The Hess Offset is displaced to the north on the east side of the Sandcherry Fault, and the distal Foy Offset continues beyond that. Little work has been published on the Foy Offset, the most detailed descriptions are found in Card and Meyn (1969) and Grant and Bite (1984). Work has been done in some detail on certain parts of the Foy Offset over the last 50 years by mining companies in the form of unpublished internal reports. However, there has been no compilation of existing Foy Offset data, and no systematic study made of the dike as a whole. Parts of the dike have not been mapped, other than at reconnaissance level in the 1940s. This especially applies to the more distal portions of the dike. The geology of rocks surrounding the dike has not been considered in any detail (e.g., Sudbury Breccia, Levack and Cartier wall rocks, etc.).

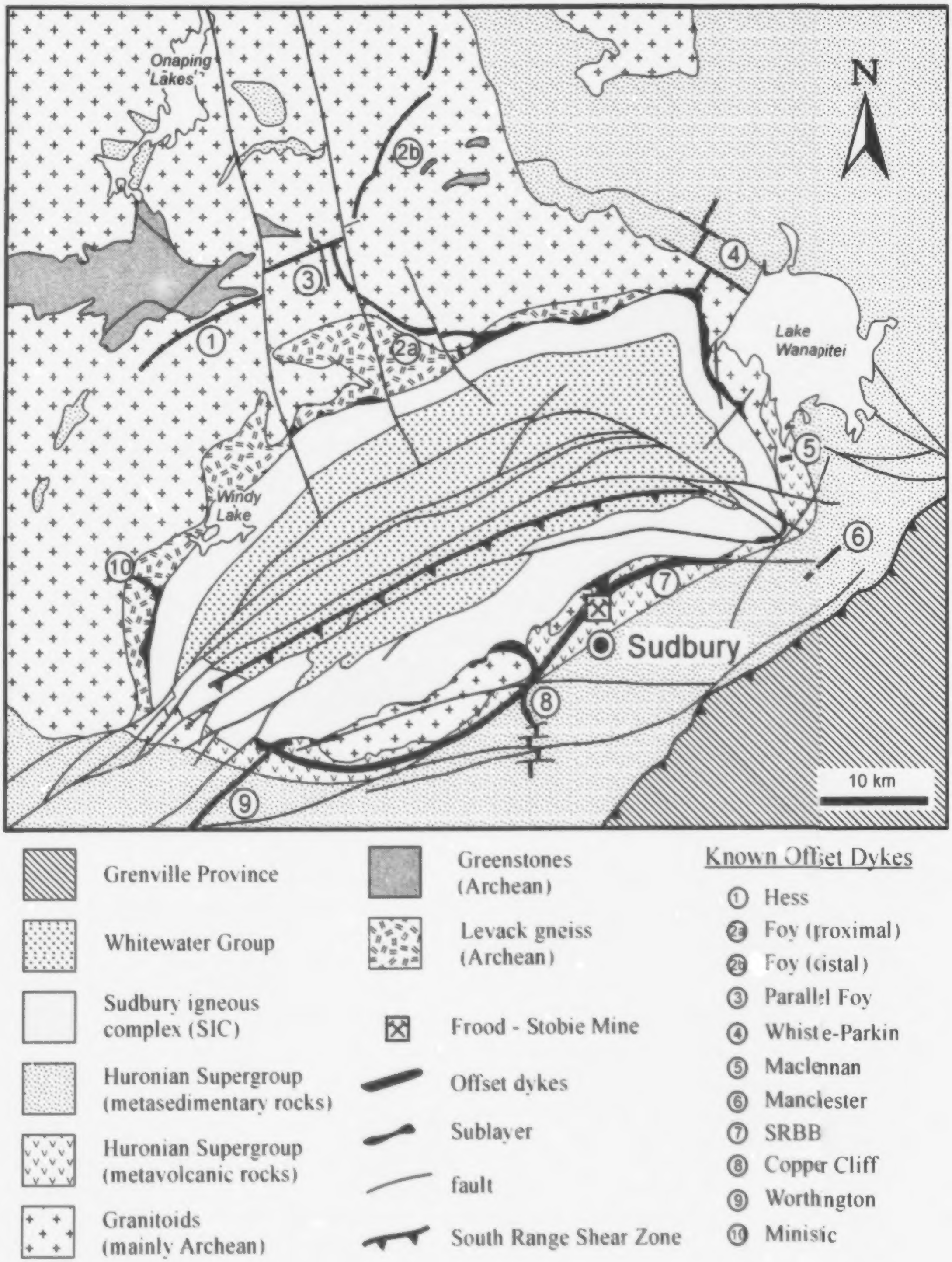

Figure 30.1. Geology of the Sudbury Igneous Complex and the location of known offset dikes.

Knowledge of these rocks will help to place the Foy Offset in its geological context and further our understanding of the offset dike emplacement process. There is an intimate association of quartz diorite with Footwall Breccia along the proximal Foy Offset, as found at Nickel Lake and Foster Lake in Bowell Township, the Nickel Offsets Mine–Foyross Lake area in Foy Township, and at the Maki showing in Tyrone Township. There is evidence for considerable northward transport of footwall lithologies by the dike. Disseminated mineralization occurs along much of the length of the Foy Offset, with the furthest known mineralization occurring in Botha Township, within the distal portion of the dike (north of the Hess Offset intersection). In contrast to many of the other offset dikes, the Foy Offset shows greater disseminated sulphide development. Work on the Foy Offset Dike started last year (1999) by MSc student Martin Tuchscherer. During the two field seasons carried out to date, a number of transects have been mapped and sampled across the Foy from proximal to distal locations. This work will contribute to revealing how the lithologies and chemistry of the dike change along strike.

WHISTLE–PARKIN OFFSET DIKE

The Whistle–Parkin Offset Dike consists of a pair of radial offset dikes, located to the northeast of the Sudbury Igneous Complex, west and northwest of Lake Wanapitei. The Whistle Offset is the proximal dike, which connects directly to the Sudbury Igneous Complex via a sublayer embayment (part of which has been mined out as the Whistle open pit). The relationship between the Whistle and Parkin offset dikes is a subject of contention. The Parkin Offset Dike is displaced west of the Whistle Offset Dike via a fault zone. As with all other offset dikes, the Whistle–Parkin Offset Dike occupies a pseudotachylyte-lined fracture-fault system, which was probably formed during the contact and compression stages of the impact event. Evidence obtained following the 1999 and 2000 field seasons indicates there is a concentric fault between the Whistle and Parkin portion of the dike, and that this fault has been responsible for their displacement and relative separation. There is considerable evidence of extensive inclusion transport along the Whistle–Parkin dike system. Fragments include Archean gneiss and granitic blocks, with associated sulphides. The project started in 1998 and is currently the focus of a PhD thesis by Alain Murphy. Mapping has been carried out at the 1:5000 scale in selected trenches along the Parkin Offset Dike, including the Milnet Mine area. This has revealed new lithologies hitherto undocumented, including: quartz diorite breccia, barren quartz diorite, inclusion-bearing quartz diorite, and radial breccia.

THE METAMORPHIC AUREOLE OF THE SUDBURY IGNEOUS COMPLEX

This year saw the start of a new project at the PhD level. Michelle Boast is studying the contact metamorphic effects around the Sudbury Igneous Complex. Field work to date has focussed on mapping and sampling transects from the Sudbury Igneous Complex into the footwall in the northwest of the structure in the vicinity of the Windy and Ministic lakes region. A total of 200 samples were taken this summer. These are currently being prepared for thin sections and geochemical analysis. The extent of the contact aureole around the Sudbury Igneous Complex is not known. Previous regional studies suggest that it is about 2 km wide (Dressler 1984) and that related hydrothermal effects extend several kilometres beyond this. Shock effects (e.g., planar deformation features) are erased within the inner 2 km, presumably due to thermal recrystallization from the hot melt sheet. Until the thermal vectors are determined in a rigorous and systematic way, halo dimensions and thermal regimes remain conjectural. Moreover, it is known that the thermal behaviour of the cooling Sudbury Igneous Complex has exerted control on Cu and PGM mineralization within Sudbury Breccia zones, which appear to have acted as conduits for post-impact fluids. A careful, well-planned investigation of these thermal effects will help to explain this mineralization and, potentially, reveal new exploration targets in the North Range. This work will also aim to establish whether the Sudbury Igneous Complex was superheated following impact, which, based on energy considerations, is considered likely.

PROJECTS AT THE COMPLETION STAGE

Theses are currently being written up by John O'Connor and Ron Scott on the Manchester and Frood–Stobie offsets. Ron Scott is due to defend by the end of 2000, and John O'Connor in 2001.

Frood–Stobie Offset Dike

The Frood–Stobie subconcentric offset occurrence is anomalous with regard to most of the other Sudbury offset dikes. It is dominated by Sudbury Breccia (pseudotachylyte) rather than quartz diorite dike material. Although quartz diorite does occur at Frood–Stobie, it is typically present as isolated pods and not dike-like sheets and quartz diorite is certainly not found as continuous bodies for any distance. It is important to realize that the Frood–Stobie Offset Dike is part of a much larger breccia belt that forms a subconcentric arc of pseudotachylyte (*see* Figure 30.1), ranging from 0.1 to over 1 km in width, and reaching about 45 km in length (Scott et al., 1996). We have termed the whole of this arc the *South Range Breccia Belt*. The South Range breccia belt abuts the Sudbury Igneous Complex in the vicinity of the Kirkwood Mine in the east (Garson Township), and at the abandoned Victoria Mine in the west (Denison Township). It also connects to the Sudbury Igneous Complex via an embayment/funnel structure in the Little Stobie and Mount Nickel mines area (Blezard Township). The belt is cut by the Copper Cliff Radial Offset Dike. Exposure is relatively good to the east of the Copper Cliff Offset (where extensive sampling has been carried out for magnetic and petrochemical work as part of our studies), but is poor to the west of it. Outcrop in Graham and Waters townships is typically limited to boulders in low-lying, marshy terrain, as originally noted by Speers (1957). However, recent mapping in this area by the Wallbridge Mining Company has revealed significantly more exposures than previously recognized. The full extent of the South Range breccia belt is partly expressed as a 120 nT high in regional aeromagnetic data. The reason for the high is not yet clear, but it is probably due to the paramagnetic susceptibilities of ferromagnesian silicate minerals that are both concentrated and aligned within the pseudotachylyte matrix (Scott and Spray 1999).

The South Range breccia belt hosts the world's largest Ni-Cu-PGE deposit, the Frood–Stobie mine complex, which has been in production for more than a century. Deposits at the Kirkwood, Little Stobie and Victoria mines have also contributed to the economic value of the belt. The Ni-Cu ore is commonly associated with quartz diorite bodies that are, in turn, hosted by the pseudotachylyte. The ores are primarily composed of massive to disseminated chalcopyrite, pyrrhotite and pentlandite, with minor associations of numerous rare platinum-group element-bearing minerals (e.g., froodite; $PdBi_2$).

The South Range breccia belt consists of subrounded to rounded, clasts and large blocks of metasedimentary and metavolcanic rocks of the 2.49–2.2 Ga Huronian Supergroup (Debicki 1990). These inclusions range from several millimetres to tens of metres in size and they are set within a dark, fine-grained crystalline matrix. The inclusions and matrix together comprise Sudbury Breccia, also known as Frood Breccia, which we now know is a form of pseudotachylyte (Dressler 1984; Thompson and Spray 1996). The matrix comprises quartz + biotite + plagioclase + K-feldspar + ilmenite, with minor pyrite and pyrrhotite. Zircon (predominantly inherited from the wall rocks) is ubiquitous and easily detected via pleochroic haloes in biotite. The matrix of the pseudotachylyte is microcrystalline, with no melt glasses being detected (if ever present). The matrix is locally massive, but is more typically found strongly foliated as defined by biotite. Magnetic studies carried out over the last two years indicate that the biotite foliation represents a primary friction melt fabric, and that it is not a metamorphic overprint formed during the Penokean (1.9–1.7 Ga) and/or Grenvillian (~1 Ga) orogenies (Scott and Spray 1999). This has interesting implications for the metamorphic history of the South Range. Previous workers have favoured amphibolite-facies grade metamorphism being realized during the later stages of the Penokean orogeny, following the impact event (Thomson et al. 1985). Our work suggests that the metamorphic grade in the South Range did not exceed greenschist-facies grade following the 1.85 Ga impact event (Scott and Spray 1999). Grades higher than this would have reset the fabric of the biotite minerals, and there is no evidence that this occurred. Those amphibolite-facies grade assemblages that do occur in the area were most probably formed during pre-impact (2.4–2.2 Ga) Blezardian tectonometamorphism (Riller and Schwerdtner 1997), or the earlier (pre-impact) stages of the Penokean orogeny. Geochronological studies are currently underway to test this. Critically, the pseudotachylyte matrix flow fabrics established for the Frood–Stobie ore region indicate that the sulphide minerals were injected subvertically. So far, no preferred *sense* of direction can be determined, but an upward flow regime is favoured.

The Frood–Stobie pseudotachylyte belt was derived by the frictional comminution and melting of wall rocks, most probably during large displacement seismogenic faulting (superfaulting, Spray 1997). Such fault behaviour may be the result of gravity-induced transient cavity collapse, which leads to the slumping of the crater walls into the impact melt sheet (Scott and Spray 2000).

Manchester Offset Dike

The Manchester Offset Dike is located 4–5 km southeast of the Sudbury Igneous Complex within Huronian metasedimentary footwall rocks. It was originally mapped as a basic to intermediate dike-like body in the 1950s (Thomson 1959), and recognized as a Sudbury Igneous Complex-related offset dike in the 1970s (Grant and Bite 1984). The quartz diorite dike is subconcentric to the Sudbury Igneous Complex and is up to 30 m wide. It strikes discontinuously for at least 10 km and dips about 60° to the southeast. A thicker, better exposed zone, approximately 5 km in length, is centred within the 10 km strip. The Manchester Offset Dike is hosted by a broad zone of Sudbury Breccia (pseudotachylyte), the southern limit of which is, in part, defined by the so-called Falcon Fault, which was generated after impact or underwent reactivation as a pre-impact lineament. The host pseudotachylyte zone is up to 350 m thick. Contacts between the pseudotachylyte and the dike are generally sharp, with the dike being slightly chilled against the pseudotachylyte. The dike comprises the assemblage quartz + plagioclase + alkali feldspar + amphibole + biotite. Granophyric and myrmekitic intergrowths are particularly common. Clinopyroxene relics also occur. The dike is a quartz diorite and, although clearly genetically related to the Sudbury Igneous Complex, is more siliceous than many of the other offsets of the Sudbury structure. This may reflect the effects of assimilating the predominantly quartzo-feldspathic (Huronian) wall rocks.

Critical to this study is the original mode of connection between the Manchester Offset and the Sudbury Igneous Complex, as there is no apparent physical attachment between the two at present exposure levels (O'Connor and Spray 1997). Penokean faulting has dismembered the Manchester Offset and field studies cannot yet constrain the dike emplacement direction (i.e., whether lateral or vertical). If a lateral connection to a radial offset cannot be found, then the implication is that Manchester was emplaced from below, or from above, via Sudbury Igneous Complex-concentric listric faulting initiated during collapse of the transient cavity some time after hypervelocity impact.

The last main field season revealed that numerous faults, related to the South Range shear zone, pass through the Manchester Offset Dike and effectively dismember it. This could account for the limited strike length as currently exposed. These faults appear to have had complicated histories, showing evidence for both strike-slip and normal or thrust displacements occurring before, during and after impact. Some were probably reactivated during the Grenvillian orogeny. The faults can show ductile deformation, in which case they are more correctly defined as shear zones. This implies that the fault-shear systems were active at depths of 10–15 km, within the brittle-ductile transition. In addition, several new outcrops of quartz diorite were found during the 1998 season, thus extending the known length of this poorly understood offset dike.

ACKNOWLEDGMENTS

This work would not have been possible without the logistical support of the Ontario Geological Survey, which is gratefully acknowledged. Funding for the University of New Brunswick Impact Geology Group's Sudbury Research Program comes from Natural Science and Engineering Research Council, Falconbridge and Inco. Thanks to undergraduates Derrick Budden, Tamara Holmes and Dino Petrakos of University of New Brunswick Geology for their field assistance during the 2000 season.

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31. Project Unit 00-31. Provincially Significant Mineral Potential Maps – The Role of the Precambrian Geoscience Section

B. Berger[1] and R. Debicki[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Land Use Policy and Planning Coordinator, Information Services Section

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INTRODUCTION

Assessment of the Province's mineral potential is a vital activity for the Ontario Geological Survey (OGS). Assessments can be used as tools to encourage exploration investment, to maximize the amount of land available for exploration, and in joint land use planning initiatives such as the *Ontario's Living Legacy* initiative for Crown land, and the development of municipal plans for private land. MNDM has engaged in the Provincially Significant Mineral Potential (PSMP) initiative to enhance its process for assessing Ontario's mineral potential, and establish an improved database to which the process can be applied.

This initiative is being undertaken now as a result of provisions in the recent *Ontario's Living Legacy* land use strategy, through which 378 new parks and conservation reserves covering almost 2.4 million hectares were announced. The provisions provide for "controlled exploration" in those parts of new parks and conservation reserves where there is "provincially significant mineral potential". Before the provisions can be implemented, areas where such mineral potential is present must be established. This initiative has two facets: 1) defining what constitutes "provincially significant mineral potential" through a multi-stakeholder committee, and 2) applying these criteria to produce a large-scale mineral resource assessment data set.

The data set is to consist of a geological theme overlain by polygons defined using the PSMP process to portray the estimated mineral potential. The Precambrian Geoscience Section (PGS) is responsible for preparing a 1:250 000 bedrock digital theme to contribute to this project. The PGS objectives are to provide to the PSMP initiative 1:250 000 bedrock geological information on a topographic base, in a GIS-ready form that builds upon and links to Earth Resources and Minerals Exploration web Site (ERMES) data sets. The Precambrian bedrock theme will be based upon existing digital Geology of Ontario manuscript maps with updating where possible within the time frame of the project. The deadline for completion of the bedrock digital theme is March 31, 2001. Past OGS compilation maps have been compiled from original map sources, and have included a thorough check of all mineral occurrences. This type of approach is not possible in the time available for completion of the PSMP geological theme. As a result, there will be **NO** hard copy maps produced from this exercise. The PSMP bedrock theme is, however, a stepping stone to meet the PGS commitment to produce an "ever-green", or continuously and readily revised compilation map series in future.

The PGS has dedicated 6 full-time geoscientists, a data manager and drafting support to the PSMP project, given the high priority and short time line. Figure 31.1 outlines the GIS technical process and Figure 31.2 shows the geological compilation process that will be employed for the PSMP project. To date, the PGS team has established the compilation process and is proceeding with the various parts of the province in the following order: 1) Boreal East, 2)Boreal West, 3) Great Lakes–St. Lawrence area, 4) North of the Boreal West region, and 5) the region beneath the Hudson Bay and James Bay Lowlands.

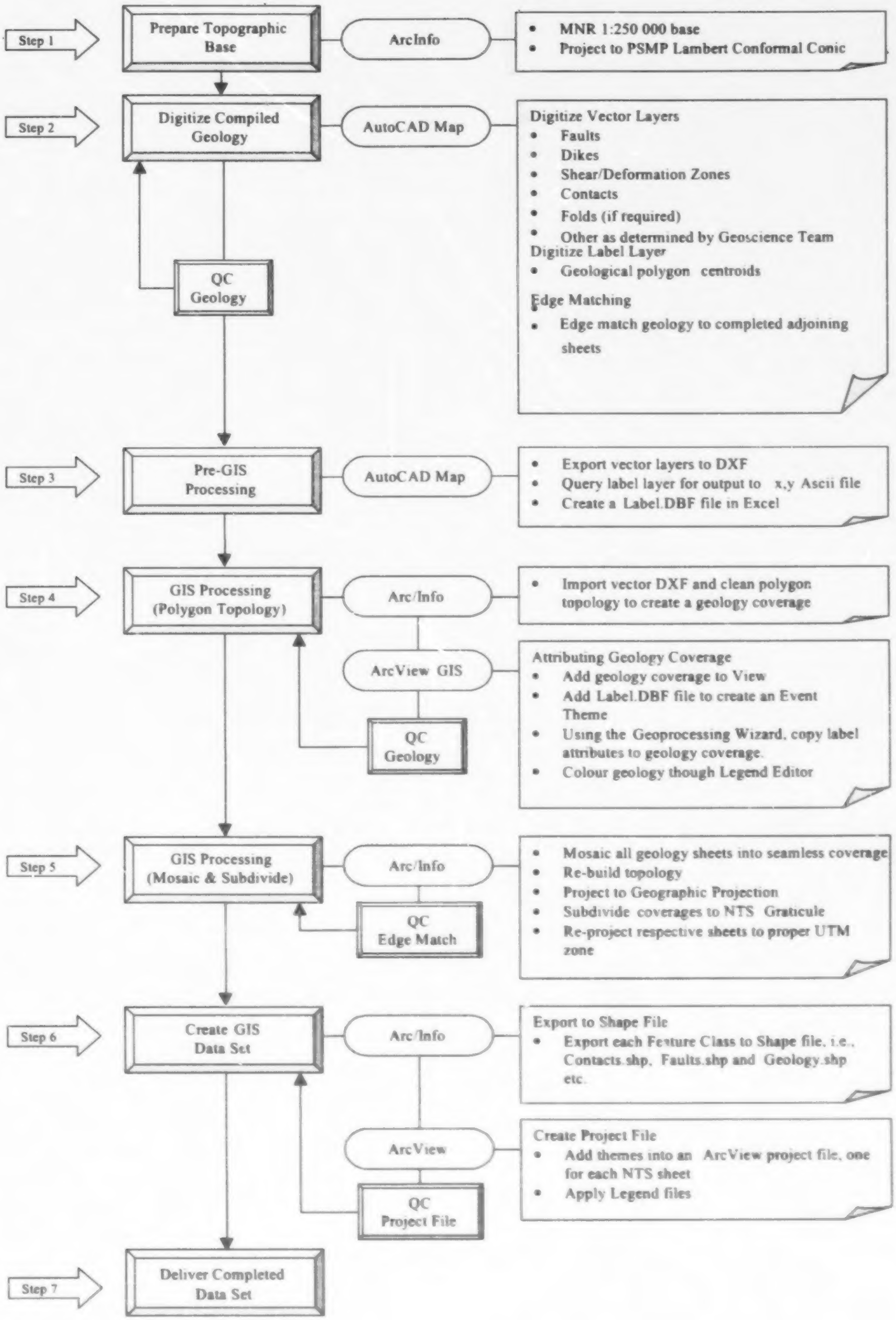
Step 1
Prepare Topographic Base
ArcInfo
MNR 1:250 000 base
Project to PSMP Lambert Conformal Conic
Step 2
Digitize Compiled Geology
AutoCAD Map
Digitize Vector Layers
Faults
Dikes
Shear/Deformation Zones
Contacts
Folds (if required)
Other as determined by Geoscience Team
Digitize Label Layer
Geological polygon centroids
Edge Matching
Edge match geology to completed adjoining sheets
QC Geology
Step 3
Pre-GIS Processing
AutoCAD Map
Export vector layers to DXF
Query label layer for output to x,y Ascii file
Create a Label.DBF file in Excel
Step 4
GIS Processing (Polygon Topology)
Arc/Info
Import vector DXF and clean polygon topology to create a geology coverage
ArcView GIS
Attributing Geology Coverage
Add geology coverage to View
Add Label.DBF file to create an Event Theme
Using the Geoprocessing Wizard, copy label attributes to geology coverage.
Colour geology though Legend Editor
QC Geology
Step 5
GIS Processing (Mosaic & Subdivide)
Arc/Info
Mosaic all geology sheets into seamless coverage
Re-build topology
Project to Geographic Projection
Subdivide coverages to NTS Graticule
Re-project respective sheets to proper UTM zone
QC Edge Match
Step 6
Create GIS Data Set
Arc/Info
Export to Shape File
Export each Feature Class to Shape file, i.e., Contacts.shp, Faults.shp and Geology.shp etc.
ArcView
Create Project File
Add themes into an ArcView project file, one for each NTS sheet
Apply Legend files
QC Project File
Step 7
Deliver Completed Data Set

Figure 31.1. PSMP GIS technical process.

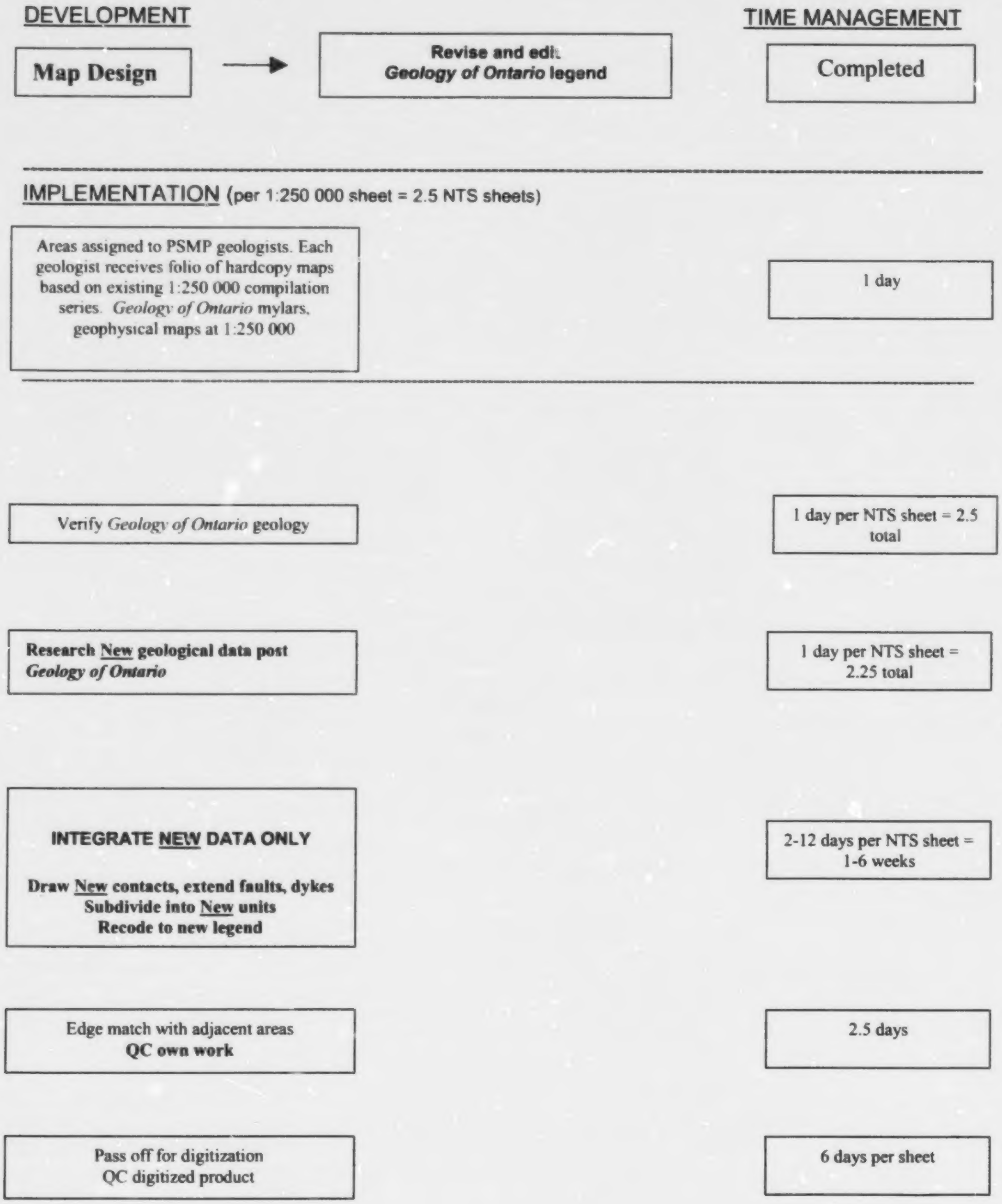
DEVELOPMENT
TIME MANAGEMENT
Map Design
Revise and edit *Geology of Ontario* legend
Completed
IMPLEMENTATION (per 1:250 000 sheet = 2.5 NTS sheets)
Areas assigned to PSMP geologists. Each geologist receives folio of hardcopy maps based on existing 1:250 000 compilation series. *Geology of Ontario* mylars, geophysical maps at 1:250 000
1 day
Verify *Geology of Ontario* geology
1 day per NTS sheet = 2.5 total
Research New geological data post *Geology of Ontario*
1 day per NTS sheet = 2.25 total
INTEGRATE NEW DATA ONLY
Draw New contacts, extend faults, dykes
Subdivide into New units
Recode to new legend
2-12 days per NTS sheet = 1-6 weeks
Edge match with adjacent areas
QC own work
2.5 days
Pass off for digitization
QC digitized product
6 days per sheet

Figure 31.2. PSMP geology compilation process.

Sedimentary Geoscience Section

32. Aggregate Resources Inventory Program Summary

D. Rowell[1] and G. Gao[2]

[1] Resident Geologist Program, Ontario Geological Survey
[2] Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Mineral aggregates, which include bedrock-derived crushed stone as well as naturally formed sand and gravel, constitute the major raw material in Ontario's road building and construction industries. Very large quantities of these materials are used each year throughout the Province. For example, in 1997, the total tonnage of mineral aggregates extracted in Ontario was 149 million tonnes or approximately 14 tonnes per capita (Ontario Ministry of Natural Resources 1999).

Although mineral aggregate deposits are plentiful in Ontario, they are fixed-location, non-renewable resources that can be exploited only in those areas where they occur. Mineral aggregates are characterized by their high bulk and low unit value so that the economic value of a deposit is a function of its proximity to a market area as well as its quality and size. The potential for extractive development is usually greatest in areas where land use competition is extreme. For these reasons the availability of adequate resources for future development is now being threatened in many areas, especially urban areas where demand is the greatest.

Comprehensive planning and resource management strategies are required to make the best use of available resources, especially in those areas experiencing rapid development. Unfortunately, in some cases, the best aggregate resources are found in or near areas of environmental sensitivity, resulting in the requirement to balance the need for the different natural resources. Therefore, planning strategies must be based on a sound knowledge of the total mineral aggregate resource base at both local and regional levels.

The purpose of the Aggregate Resources Inventory Program is to provide the basic geological information required to include potential mineral aggregate resource areas in planning strategies. The reports should form the basis for discussion on those areas best suited for possible extraction. The program aim is to assist decision-makers in protecting the public well-being by ensuring that adequate resources of mineral aggregate remain available for future use.

The aggregate resources for the majority of southern Ontario and many of the more populated areas of northern Ontario have been mapped. Most of the maps and associated reports describing these resources are on a township level and are greater than 20 years old. Re-mapping of some of these areas is currently underway to reflect land use changes and resource depletion. All inventories currently being undertaken by the OGS cover entire regional municipalities or counties. Five project areas, occupying over 1.8 million ha, are currently being completed by Sedimentary Geoscience Section (SGS) staff (Figure 1).

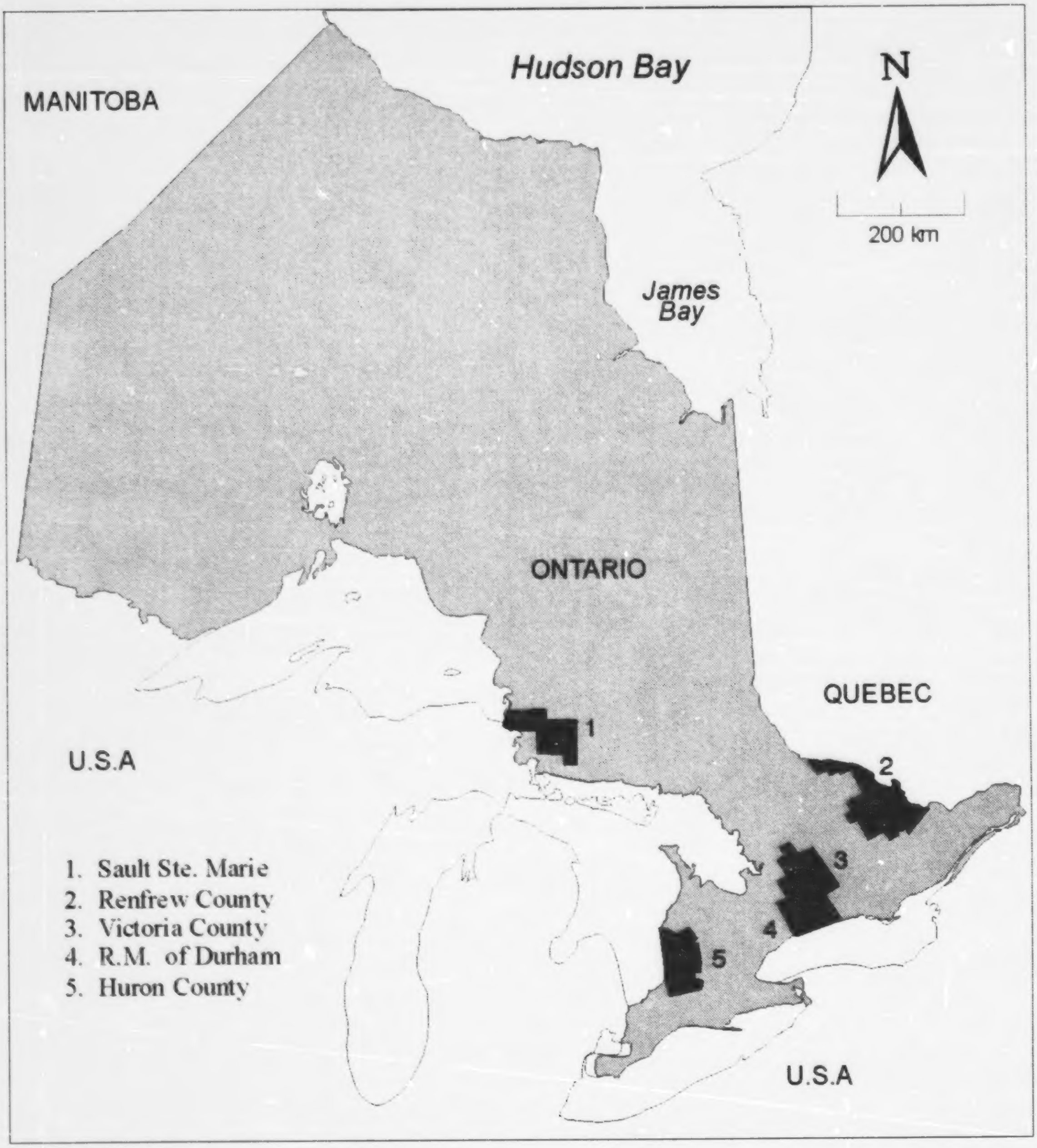

Figure 1. Location of Aggregate Resources Inventory Program Projects

PROJECT AREAS

In 2000, field work was completed on an aggregate resource assessment of 17 townships surrounding the City of Sault Ste. Marie. This 2 year project, started in 1999, covers a study area of approximately 170 000 ha and is covered by parts of the Ile Parisienne (41K/10), Pancake Bay (41K/15), Searchmont (41K/16), Sault Ste. Marie (41J/9), Echo Lake (41J/12) and Ranger Lake (41J/13) 1:50 000 scale map sheets of the National Topographic System (NTS) (Rowell 1999). These townships were recently designated under the *Aggregate Resources Act (ARA) 1989*. The final report and maps should be completed by early 2001.

A multi year aggregate resources inventory project was completed in 2000 for the County of Renfrew. Renfrew County occupies 763 870 ha along the Ottawa River northwest of Ottawa. This project was contracted to MacNaughton Hermsen Britton Clarkson Planning Limited with supervision and field checking provided by SGS staff. The final report and maps should be available in late 2000.

An aggregate resource inventory for Victoria County was released in September 2000. Victoria County occupies 306 690 ha in south-central Ontario. The report was completed under the supervision of D. Rowell. Victoria County contains large resources of sand and gravel in the Oak Ridges Moraine which is located in the southern most township in Victoria County (Manvers Township). Additionally, there is the potential of large quantities of bedrock-derived aggregates from the Carden Plain; this limestone plain traverses the north-central part of Victoria County. The Gull River and Bobcaygeon formations within the county provide an excellent source of good quality aggregate.

As a result of recent detailed surficial mapping covering the Regional Municipality of Durham, an updated aggregate inventory is being completed. The report and maps, incorporating this information, are expected in late 2000 and will cover an area of approximately 242 184 ha.

During the summer of 2000, an aggregate resources inventory was started in Huron County. Huron County occupies 340 273 ha along the shoreline of Lake Huron. The county is in the process of developing their official plans and requested an inventory of aggregate resources. The work started in August and the report and maps are expected in 2001.

OTHER ACTIVITIES

In 1999, staff from the Sedimentary Geoscience Section were contracted to complete an abandoned pit and quarry inventory for the Aggregate Producers Association of Ontario (APAO). The first part of the survey, completed in the fall of 1999, included: the Sault Ste. Marie area; part of the District of Sudbury; Grenville County; and the United Counties of Stormont, Dundas and Glengarry. Phase two of the work, covering Elgin County and the Regional Municipality of Halton, was completed in the spring of 2000.

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33. Project Unit 99-017. Quaternary Geology Mapping and Overburden Sampling, Schreiber Area, Northwestern Ontario

T.F. Morris[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Ontario Geological Survey (OGS) has defined the Kapuskasing Structural Zone (KSZ) (Figure 33.1) as an area of high potential for diamond exploration. The potential for diamonds has been established through overburden mapping and sampling programs that defined the types, concentrations and distribution of several important kimberlite indicator minerals (KIMs) (Morris et al. 1994; Morris et al. 1997; Morris, Breaks et al. 1998; Morris et al. 1998; Stephenson et al. 1999). Kimberlite is a rock type commonly recognized as the primary host for diamond. KIMs are a suite of heavy minerals (specific gravity greater than 3.2) associated with kimberlite (Cr-pyrope garnet, chromite, Mg-rich ilmenite, Cr-diopside and forsteritic olivine). Since release of the OGS studies, diamond-bearing rock and kimberlite have been discovered in the Wawa area (KWG Resources Inc./Spider Resources Inc., Press Releases, 20/08/97 and 31/07/00; CANABRAVA Diamond Corporation, Press Release, 09/12/97; Band-Ore Resources Ltd., Press Release, 02/05/00; Pele Mountain Resources Inc., Press Release, 07/07/00; Dumont Nickel Inc., Press Release, 21/08/00).

Following the success of the Quaternary mapping and overburden sampling programs over the KSZ, similar programs have been undertaken over a part of the Trans-Superior Tectonic Zone (TSTZ) to evaluate its potential to host kimberlite (Morris 1999). The TSTZ extends from Michigan north-northeast into Ontario west of Marathon (Figure 33.1). Kimberlites straddle the structure within Michigan (Cannon and Mudrey 1981) and ultramafic lamprophyres, which may belong to the kimberlite "clan" (Rock 1990), are recognized in association with the TSTZ within Ontario (Sage 1993). The TSTZ represents a fault system that has accommodated emplacement of mantle material (Sage 1999). In addition, the TSTZ is located within an Archean craton and is associated with a dike swarm (mantle-root friendly structure); conditions that are favorable for kimberlite emplacement and diamond preservation (Morris and Kaszycki 1997).

During the 1999 field season the focus of field investigations in the TSTZ centered on the Killala Lake-Coldwell area (Morris 1999). This area is represented on 2, 1:50 000 scale map sheets of the National Topographic System (NTS). The northern part of the study area is covered by the Killala Lake (42 E/2) sheet and the southern part by the Coldwell (42 D/15) sheet. The area is bounded by longitudes 86°30′W and 87°00′W and latitudes 48°45′N and 49°15′N. From the Quaternary geology mapping and overburden sampling, several excellent kimberlite exploration targets were defined (Morris et al. 2000).

In addition to KIMs, overburden samples from the 1999 field season were processed for metamorphic or magmatic massive sulphide indicator minerals (MMSIMs®), gold grains and carbonatite indicator minerals. The MMSIMs are associated with 3 main types of base metal deposits: 1) volcanosedimentary massive sulphides in high grade regional metamorphic terrain; 2) skarn and greisen deposits; and 3) magmatic Ni-Cu sulphides (Averill 1999). The composition of gahnite, a rare and

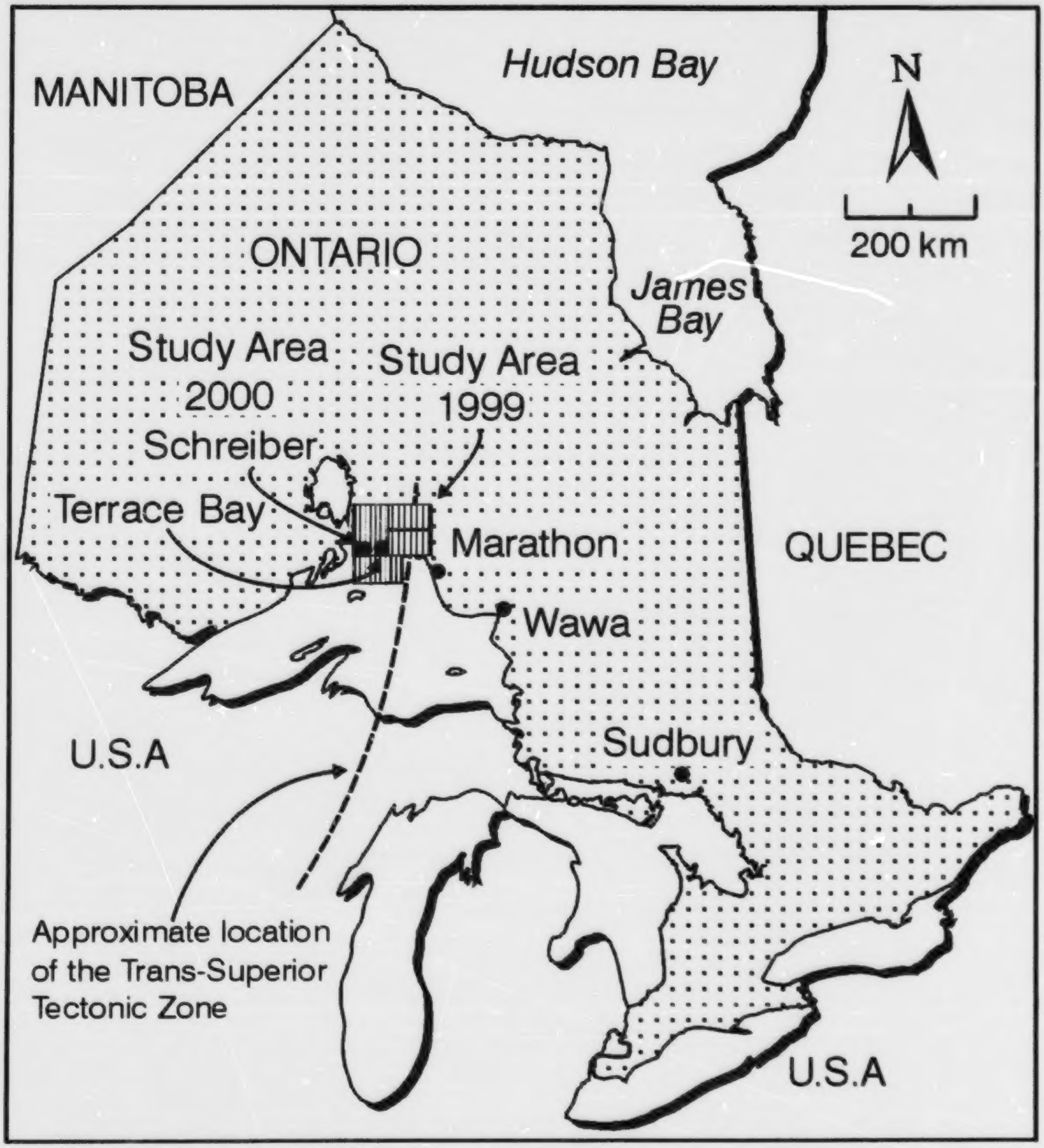

Figure 33.1 Location of Trans-Superior Tectonic Zone relative to study area

important MMSIM associated with metamorphosed volcanosedimentary massive sulphide deposits, can also be used to indicate the presence of rare-element pegmatite (Morris, Breaks et al. 1997).

Although an anomalous number of gold grains recovered from a sample is important, the shape of gold grains is also determined to estimate the distance of gold grain transport from source (DiLabio 1990). Shape classification includes: pristine (little to no modification of gold grain shape suggesting "close" proximity to source); modified (moderate modification of gold grain shape suggesting "moderate" distance of transport from source); and reshaped (gold grain shape reshaped from original form indicating "long" distance of transport from source).

Several heavy minerals associated with carbonatite were also recovered from the 1999 overburden sampling program (Morris et al. 2000). The most important of these include barite, synchysite and bastnaestite. The significance of these 3 heavy minerals is that they are associated with the mineralogy found at the Molycorp Mountain Pass Carbonatite, a former major supplier of rare earth metals to the world (Morris et al. 2000).

The focus of field investigations for the 2000 field season shifted west to cover the western edge of the TSTZ. This area is represented on 2, NTS 1:50 000 scale map sheets. The northern part of the study area is covered by the Dickison Lake (42 E/3) sheet and the southern part by the Schreiber (42 D/14) sheet. The area is bounded by longitudes 87°00′W and 87°30′W and latitudes 48°45′N and 49°15′N. In addition, the Slate Islands were also mapped and modern alluvium and till samples taken. The Slate Islands are represented on 2, NTS 1:50 000 scale map sheets. The western part by the Slate Islands (42 D/11) sheet and the eastern part by the Pic Island (42 D/10) sheet. This area is bounded by longitudes 86°55′W and 87°06′W and latitudes 48°36′N and 48°42′N. All overburden samples collected during this study will be processed for KIMs, MMSIMs, gold, carbonatite and Platinum Group Minerals (PGMs).

PHYSIOGRAPHY

The study area is located south of the Great Lakes-Hudson Bay drainage divide and all surface drainage flows south into Lake Superior. There are 5 major drainage basins within the study area. Flow from these basins is through the Pays Plat, Whitesand and Aguasobon rivers and the Big Duck and Blackbird creeks.

Much of the area lies within the Abitibi Uplands subregion of the James physiographic region (Bostock 1976). This region is underlain by crystalline Archean rocks and characterized by a broad rolling surface that rises gently from the Hudson Bay Lowland. Locally, several distinctive cross-cutting faults occur. The Gravel River-Kamuck River fault is the most prominent of these with a floor width averaging 60 m and vertical valley walls up to 150 m high (Carter 1988). Along the shoreline of Lake Superior the study area falls within the Port Arthur Hills subregion of the James physiographic region (Bostock 1976). This subregion consists of massive and rugged hills with relief in excess of 150 m (Gartner 1979a).

BEDROCK GEOLOGY

Most of the study area straddles a complex suite of rocks associated with the Quetico and Wawa subprovinces of the Canadian Shield (Harcourt 1939; Mason 1981a, 1981b, 1981c; Carter 1988; Ontario Geological Survey 1991). Both subprovinces consist of Neo-Mesoarchean (2.5-3.4 Ga) intrusive and supracrustal rocks. Several islands within Lake Superior are included in the study area. The bedrock of these islands, and in places along the north shore of Lake Superior, consist of Late Precambrian (1086-1107 Ma) to Middle Precambrian (1.6-2.5 Ga) sedimentary rocks.

Neo-Mesoarchean intrusive bedrock of the Quetico subprovince consists of a gneissic tonalite suite, muscovite-bearing granitic rocks and massive granite to granodiorite rocks. Quetico supracrustal bedrock consists of a metasedimentary suite. Neo-Mesoarchean intrusive rocks of the Wawa subprovince include a massive granodiorite to granite suite, a gneissic tonalite suite and mafic and ultramafic rocks (gabbro, anorthosite, ultramafic). Wawa subprovince supracrustal rocks of the same age include a metasedimentary suite, felsic to intermediate metavolcanic rocks and mafic to intermediate metavolcanic rocks.

Along the north shore of Lake Superior there are 2 areas within the study area of sedimentary rock belonging to the Gunflint Formation of the Middle Precambrian (1.6-2.5 Ga) Animikie Group (Carter 1988). Offshore, several islands consist of sedimentary rocks belonging to the Late Precambrian (1086-1107 Ma) Sibley Group (Ontario Geological Survey 1991).

Crosscutting these rocks are at least 2 different dike swarms. The oldest is the Marathon Dike swarm, striking northeasterly and emplaced around 2.17 Ga (Osmani 1991). The younger, Pukaskwa Dike swarm, is related to the volcanic rocks of the Keewenawan Supergroup that were deposited within the Midcontinent Rift between 1109 and 1086 Ma (Osmani 1991).

The study area straddles the western edge of the TSTZ. This is a prominent structural feature that extends north-northeast from Michigan where several kimberlites occur. This tectonic zone was emplaced between 1.0 to 1.2 Ga (Sage 1991).

QUATERNARY GEOLOGY

All glacial landforms and related materials within the study area were deposited during the Wisconsinan glaciation. Mapping of Quaternary materials has been completed at a scale of 1:1 000 000 (Barnett et al. 1991), 1:506 880 (Zoltai 1965) and 1:100 000 (Gartner 1979a, 1979b). Specific studies or observations on local Quaternary features and landforms have been completed by Geddes et al. (1987), Phillips (1980) and Zoltai (1967).

The last glacial ice flow across the study area varied between 165°-238° with an average of 194°. Direction of ice flow is defined by the orientation of striae, grooves, chattermarks and streamlined bedrock. In general, more southerly flow was restricted to bedrock controlled troughs such as those associated with the Aguasabon River and Long Lake, whereas more southwesterly flow occurred across topographically higher terrain. Unlike the area immediately to the east, cross-cutting striae were not observed. To the east, a younger set of southerly orientated striae were attributed to a late ice flow associated with thinning of the ice sheet. An older more southwesterly orientated set of striae were attributed to the established, regional flow (Morris 1999). A basal till (< 1 m) deposited by regional ice flow covers most of the study area. The clasts within the till reflect local bedrock lithologies and the matrix does not react with 10% HCl.

Landforms and materials associated with ice margin retreat are located primarily within bedrock controlled valleys. Ice-contact stratified drift is associated with recessional moraines, dead-ice topography, eskers and valley fill deposits. Within recessional moraine, dead-ice topography and valley fill, flow till (with well developed flow structure) and poorly-sorted pebbly sand, containing a variety of clast types (from local material to Hudson Bay derived Paleozoic clasts), were observed. The matrix of this material reacts strongly with 10% HCl. Several well-developed eskers occur within the Long Lake valley. Several sections through these eskers reveal well-sorted sand and coarse gravel.

Glaciofluvial channel deposits consisting of well sorted sands to coarse boulders, of primarily local provenance, were identified within several narrow bedrock controlled valleys. Glaciolacustrine materials were deposited within 2 different environments. Within the Dickison Lake sheet, straddling the Wintering Road, fine textured sand was deposited where glacial meltwater was trapped between the ice margin and local topographically higher ground. Closer to Lake Superior, coarse-grained glaciolacustrine materials were deposited within bedrock controlled valleys, associated with historic lake levels of the Lake

Superior basin (Farrand 1960). The elevation of each of these lakes is defined by terrace surfaces, beach ridges and wave-cut benches. Post-glacial features such as colluvium and modern shoreline features (such as bars and spits) were also observed.

PROJECT STATUS

To date, 236 modern alluvium samples have been submitted for gold grain, KIM, MMSIMs, carbonatite and PGM analysis. The distribution of these samples provides an excellent regional coverage of the area. Analytical results from a series of orientation surveys and bedrock samples collected during last year's study will provide information critical in assessing the heavy mineral data derived from the current modern alluvium sampling program (Morris et al. 2000). Amalgamating the data derived from the current sampling program with that of last year will provide an excellent assessment of the region's mineral potential.

Six additional modern alluvium samples were collected for gold grain assessment and have been submitted for analysis. Three of the samples were collected from Cameco's Empress Hill gold property, to verify gold values obtained from last year's orientation survey and to determine the source of the gold grains within the modern alluvium samples (Morris et al. 2000). All other 3 samples were collected from the Hays Lake aggregate pit to evaluate previously reported gold values (Holbrooke 1939; Smyk and Schneiders 1995).

A total of 54 till samples were collected. Site selection was determined through the use of a hypothetical 5 km^2 grid that was placed over the study area and as many of these grids sampled for till as was possible. At each of the 54 till sample sites, 250g samples of humus, "B" and "C" horizon till material were collected for geochemical analysis. A 10 kg bulk sample of "C" horizon material was also collected and will be processed for heavy minerals.

Clast lithologies have also been determined for all modern alluvium and till samples collected. This information is essential in determining proximity to source for heavy mineral and geochemical signatures. Quaternary geology mapping is ongoing.

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34. Project Unit 00-037. Regional Modern Alluvium Sampling Survey of the Temagami-Marten River Area, Northeastern Ontario

S. E. Allan[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Temagami-Marten River area of Northeastern Ontario (Figure 34.1) has been a historical site of mining operations. Past base metal producers include the Temagami Island Mine and the Kanichee Mine, while an iron formation in the area was exploited by the Sherman Mine. Numerous sulphide showings are known throughout the area (Bennett 1978), as well as a small number of arsenic deposits. In more recent years, the discovery of kimberlites to the north of the survey area in New Liskeard and Kirkland Lake has triggered an increase in diamond exploration across the region. The Lake Temiskaming Structural Zone lies directly to the northeast of the study area, striking almost parallel to its east and west boundaries. This feature, trending northwest at approximately 325°, appears to be the structural zone through which kimberlites intruded (Sage 2000). The Net Lake Fault, believed by Lovell and Caine (1970) to be part of the Lake Temiskaming Structural Zone, lies within the northeastern section of the study area. Intersections of orthogonal structures, such as the Grenville Front, with this series of northwest-trending faults present potential settings for kimberlitic emplacement and therefore heightens the interest for exploration in this area. Additionally, the lifting of the Lake Temagami Land Caution has opened areas previously closed to staking.

The main focus of the present study is to determine the distribution of kimberlite indicator minerals (KIMs) in the area. Kimberlite is a rock type recognized commonly as the primary host for diamond. The KIM suite of minerals includes pyrope and eclogitic garnets, magnesian ilmenite, chromite, chrome diopside, forsteritic olivine and diamond. The presence of these indicator minerals will be used to determine the prospect of and proximity of any potential diamond-bearing kimberlites in the vicinity. The occurrence of magmatic massive sulphide indicator minerals (MMSIM®), gold and platinum/palladium indicator minerals will also be investigated.

The Temagami-Marten River study area is represented on 7 1:50 000 scale National Topographic Systems map sheets. The northern section is covered by the eastern half of the Obabika Lake (41 P/1) and the western half of the Temagami (31 M/4) sheets. The central area comprises the eastern half of the Lake Temagami (41 I/16) and the Ingall Lake (31 L/13) sheets. Coverage in the south comprises the eastern quarter of the Glen Afton (41 I/9), the Marten Lake (31L/12) and the western quarter of the Temiskaming (31 L/11) sheets.

PHYSIOGRAPHY

The study area falls within the Cobalt Plain and the Laurentian Highlands physiographic divisions, with the majority lying in the former (Bostock 1976). The Cobalt Plain region dominates the north-

northwest portion of the shady area and is characterized by low hummocky terrain of Precambrian bedrock disrupted by north trending ridges of younger intrusive units that attain elevations of up to 180 m asl. Rock escarpments and steep sided gullies are prominent throughout the landscape, with swamps and creeks occupying lower lying areas. Drainage patterns are controlled by structural features of the bedrock as evidenced by the linear and rectilinear forms of lakes (Bennett 1978). To the south-southeast, the Laurentian Highlands controls drainage patterns and is characterized by rugged terrain with elevations reaching 460 m asl.

Two drainage basins, Lake Nipissing and Lake Temiskaming, are represented in the study area. Drainage from lakes and streams in the northwestern section first enters Red Squirrel Lake and then Lake Temagami, the largest water body within the region. The southerly direction of water flow continues to the southwestern part of the area and forms part of the drainage basin of Lake Nipissing. Water bodies in the northeastern part of the study area drain toward Lake Temiskaming, located to the east of the region. In the southeast, streams and lakes flow either toward Lake Temiskaming and the Montreal River, or towards the Tomiko River, Tomiko Lake and then on to Lake Nipissing.

GENERAL GEOLOGY

Within the study area lies the intersection of the 3 main provinces of the Canadian Shield – the Superior, the Southern and the Grenville (Figure 34.1). Separating them is the Grenville Front, which divides the area into a northern zone consisting of the Southern and Superior Provinces, and a southern zone consisting of the Grenville Province. The main lithologic units in the study area are of Precambrian age and are overlain by a thin layer of Pleistocene glacial and glaciofluvial deposits as well as Recent lake, swamp and river deposits (Simony 1964).

In the north, the Archean Superior Province consists of intrusive and supracrustal rocks. The intrusives consist of a granitic plutonic suite, a foliated tonalite suite, and mafic and ultramafic rocks of the Neo-to Mesoarchean (2.5 to 3.4 Ga). These suites are part of units formerly called Algoman and Temiskaming (Ontario Geological Survey 1991). Supracrustal rocks of the same age include felsic to intermediate and mafic to intermediate metavolcanic suites both of which include minor metasedimentary and intrusive rocks, as well as related migmatites and iron formations. These suites were formerly classified as the Keewatin Unit (Ontario Geological Survey 1991; Bennett 1978).

The Southern Province comprises the Cobalt Group of the Paleoproterozoic (2.2 Ga to 2450 Ma) Huronian Supergroup, specifically the Gowganda and Lorrain formations. The Gowganda Formation is composed of polymictic paraconglomerate, minor pebble and boulder conglomerate, sedimentary breccia, greywacke, siltstone, argillite, feldspathic quartzite, and arenite (Bennett et al. 1991; Bennett 1978). The Lorrain Formation contains quartzite, quartzite breccia, arkose and greywacke (Simony 1964). Intruding the Huronian Supergroup are swarms of dikes and sills of the Nipissing Diabase (2219 Ma); the rock types associated with these intrusions consist of quartz diabase, gabbro, pegmatitic, gabbro and diorite (Bennett 1978). A series of Mesoproterozoic (0.9 to 1.6 Ga) northwest-trending dikes intrude the earlier formations and are made up of olivine diabase (Sudbury type – 1238 Ma), granophyric diabase, porphyritic diabase, intrusive breccia and lamprophyre (Bennett 1978; Ontario Geological Survey 1991).

The Mesoproterozoic rocks of the Grenville Province, specifically those belonging to the Central Gneissic Belt, occupy the southern portion of the study area. Various types of suites are found in the area including: felsic igneous rocks and their derived gneisses; migmatites and a range of gneisses consisting of layered biotitic-, quartzofeldspathic-, ortho- and paragneisses, and gneisses of metasedimentary origin (Ontario Geological Survey 1991).

In the central part of the area, the occurrence of a Paleozoic carbonatite dike has been reported by Bennett (1978). The structure is 10 to 20 cm wide and strikes north-northeast and is possibly of Cambrian age.

QUATERNARY GEOLOGY

During the Pleistocene (1.6 to 0.01 Ma) the study area was affected by the Labrador sector of the Laurentide Ice Sheet. Typically, glacial ice advanced south-southwestward originating in Quebec and Labrador (Barnett 1991). Glacial striae indicate 3 different stages of ice flow direction. The oldest, a west-southwest flow, is represented by striae oriented between 215° to 275°, with a median of 240°. Striae oriented in the range of 180° to 210° indicate an intermediate south-southwest flow. The latest regional ice flow, trending in a south-southeast direction (130° to 170°) overprints the previous 2 (Veillette 1986). The surficial deposits in the region are thought to have been deposited primarily during the Late Wisconsinan substage. Glacial processes eroded and scoured the area to reveal bedrock-dominated terrain and a thin discontinuous layer of till was deposited. This till is poorly sorted; unstratified, sandy to silty with a high content of pebbles, cobbles and boulders which reflect the composition of underlying rocks (Boissonneau 1968; Roed 1979).

By the beginning of the Holocene, 10 000 years ago, deglaciation in the region was well underway. Glaciofluvial deposits, in the form of ice-contact and outwash deposits, formed in contact with and distal to the ice mass. Glaciofluvial ice-contact deposits are primarily in the form of eskers which consist of sand and gravel and have narrow crests and steeply sloping sides (Boissonneau 1968). Other remnants of glaciofluvial activity in the area are proglacial river and deltaic deposits, and subaqueous fan deposits (Barnett et al. 1991). In the southeast a major recessional moraine, the McConnell Lake Moraine, was deposited when ice flow halted at the south end of Lake Temiskaming. A few smaller moraine and kame deposits are found in the region associated with breaks in the retreat of the ice margin (Gartner 1980). Additionally, swamp, lake and stream deposits of the Recent, as well as patches of organic peatland deposits, are found in the area (Simony 1964; Bennett 1978; Sado and Carswell 1987).

REGIONAL SAMPLING PROGRAM

The current survey was conducted in July and August 2000, and covered a total area of approximately 3619 km^2. A total of 256 modern alluvium samples were collected. A grid spacing of 4 km^2 with lines oriented north and east was used to locate samples in the field. Owing to the nature of the survey, i.e., stream sediment sampling, samples were taken from streams as close to grid intersections as possible. In general, all grid squares were sampled at least once and the resulting distribution provides excellent regional coverage. Access to sample locations was achieved by truck, boat or float plane. The position of each sample was accurately recorded with a Global Positioning System (GPS) instrument and NTS map sheets.

Within streams, longitudinal and point bars, boulder, log and vegetation traps were targeted for sample collection as these are points of heavy mineral deposition. Sample size ranged from 10 kg up to 20 kg. Larger samples were collected at some sites to compensate for dilution of heavy mineral grains by the high percentage of organic material found in streams in the area. Samples were sieved in the field using a 5 mm mesh screen. The <5 mm fraction of the sample has been sent for heavy mineral processing to determine the presence of KIMs and any other indicator minerals. Of the coarser fraction, approximately 55 pebbles were collected from each sample, where possible. Lithological studies for each sample are presently being completed. To date, pebble lithologies indicate that, typically, stream deposits are locally derived.

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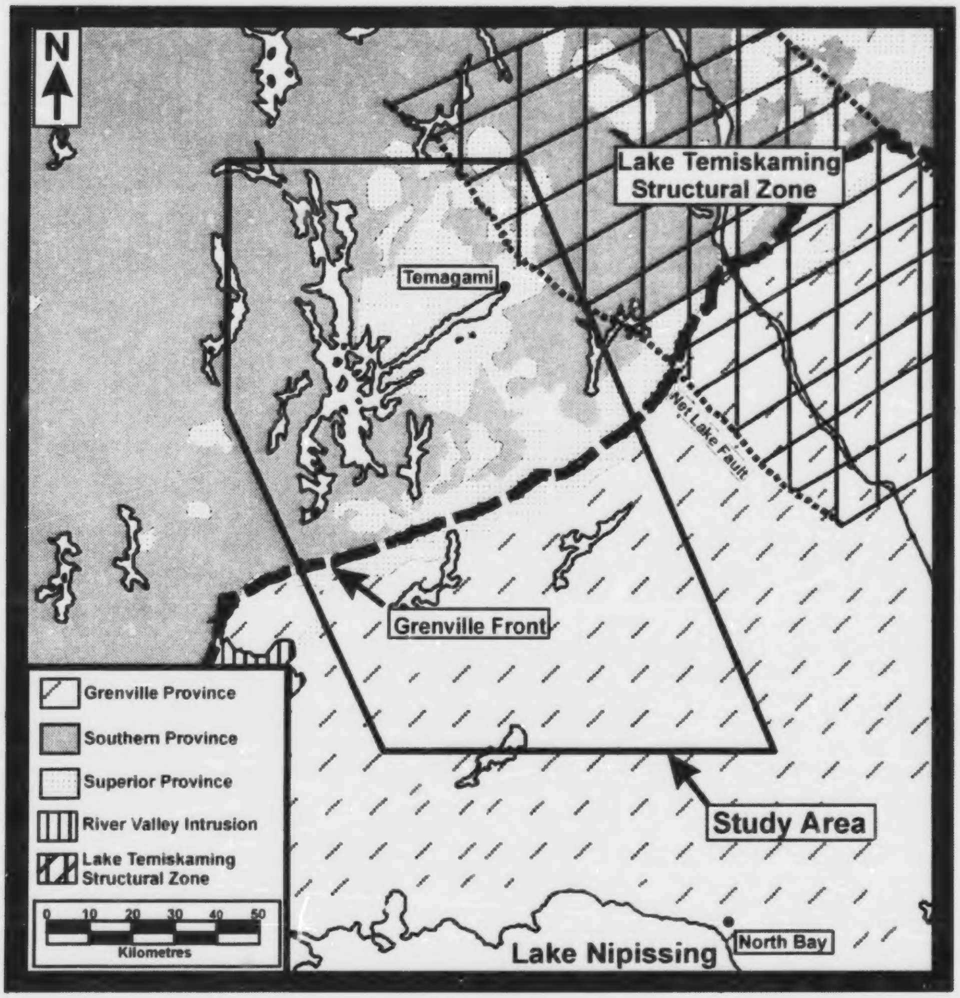

Figure 34.1. Location and general geology map of study area.

35. Project Unit 00-35. Drift Exploration for PGEs, Northwestern Ontario

C.A. Searcy[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

In recent years exploration interest for platinum group elements (PGEs) has increased significantly across northern Ontario due largely to dramatic price increases for these commodities. This increase in price is attributed largely to an increased demand by the automobile industry. Palladium is a prime component in the production of catalysts that are needed to meet tougher emission standards. An additional reason for increased PGE exploration in northern Ontario is the beginning of commercial production at North American Palladium Ltd's Lac Des Iles Mine in 1993. The mine, located approximately 85 km north of Thunder Bay (Figure 35.1), is the largest producer of palladium in Canada (North American Palladium Ltd's http://www.napalladium.ca).

The objective of the present project is to sample surficial materials in areas of known PGE occurrences to assess the application and usefulness of surficial sampling for PGE exploration. Eight project areas in northwestern Ontario were selected for orientation studies (Figure 35.1). At 6 of these study sites samples were collected at a spacing of 25 m along transect lines. Two regional studies were done with samples taken at a spacing of 200 m along each transect line. Materials sampled were C-horizon till, B-horizon soil, humus and vegetation. These samples will be processed and analyzed for platinum group elements (PGEs), gold, base metals, kimberlite indicator minerals (KIMs) and metamorphic or magmatic massive sulphide indicator minerals (MMSIM®). MMSIM® mineralogy is described by Averill (1999).

STUDY AREAS

Samuels Lake

The Samuels Lake property, currently being explored by Starcore Resources Ltd., is located approximately 45 km southwest of Atikokan, Ontario. PGEs, as well as nickel and copper, have been discovered in a late Archean, mafic-ultramafic complex (Pettigrew et al. 2000). As thin glacial drift was not till, it was not sampled. The last glacial ice flow direction as determined by glacial striations was 200°. Six humus samples and 6 vegetation samples were collected on the peninsula where rock chip sample assay values have returned a weighted average of 4.1 g/t platinum, palladium and gold combined (Starcore Resources Ltd. Samuels Lake Property Report, http://www.starcore.com).

Nym Lake

The Nym Lake property is located approximately 15 km southeast of Atikokan, Ontario. This Archean, ultramafic intrusion (Schnieders et al. 2000) has been drilled by Band-Ore Resources Ltd. Of 6 grab samples collected by the company along a 200 m portion of the intrusive, 1 sample assayed at 3 g/t combined Pt and Pd and all but 1 assayed in excess of 1 g/t combined Pt and Pd (May 3, 1999 press release http://www.band-ore.com). The property is bedrock dominated with a thin cover of till. Glacial striations indicate the last ice flow direction across the area was 200°. Twenty-four sample sites, spaced at 200 m intervals along 7 transect lines, were positioned over the area of the mafic intrusion and related breccia. The number of samples collected on the Nym Lake Property for each sample media are: 24 humus; 24 B-horizon soil; 22 C-horizon till for fine fraction (-63µ) geochemical analysis and 18 C-horizon till for analysis of heavy mineral concentrate (HMC).

Haines Township

The Haines Township property, located approximately 8 km northwest of the Shebandowan Mine site, is being explored by J. and J. Hackl and is optioned to LMX Resources Ltd. The property overlies the Late Archean Haines Gabbro (Ontario Geological Survey 1991). The area sampled is bedrock dominated with a thin cover of till. Samples were collected along 5 transect lines, all located over sites that produced assay results in excess of 300 ppb PGE combined (J. Hackl, prospector, personal communication, 2000). The sampling lines were aligned parallel with the last glacial ice flow direction as determined from glacial striations on the property. Glacial striations are orientated between 220° and 240° and average 226°. Sample sites along transect lines were spaced at 25 m intervals. The number of samples collected on the Haines Township Property for each sample media are: 50 humus; 45 B-horizon soil; 31 C-horizon till for fine fraction (-63µ) geochemical analysis; 10 C-horizon till for HMC analysis and 6 vegetation.

Buck Lake

Buck Lake Ventures Ltd. and LMX Resources Ltd. are currently exploring a property on the north shore of Buck Lake, situated approximately 28 km west of the Lac Des Iles Palladium Mine. The mineralized bedrock is Late Archean brecciated gabbro (Schnieders et al. 2000). The first channel saw sample taken on this property by Buck Lake Ventures Ltd. assayed at 538 ppb Pt, Pd and Au over 46 m (Buck Lake Ventures Ltd. Press Release, June 22, 2000). The terrain is dominated by a thin cover of till over bedrock; glacial striations indicate the last ice flow direction to be 240°. Transect lines were established parallel to ice flow direction and samples were collected at 25 m intervals from 425 m down-ice to 225 m up-ice from the mineralization. The number of each sample media collected on the Buck Lake Property are: 28 humus; 28 B-horizon soil; C-horizon till for fine fraction (-63µ) geochemical analysis and 7 C-horizon till for HMC analysis.

Lac Des Iles – Baker Zone

North American Palladium Limited's Lac Des Iles Mine site is located 85 km north of Thunder Bay, Ontario. On the Lac Des Iles Mine site property, 2 separate case studies were completed. The first being the Baker Zone, which is an area elevated in PGE mineralization within the mafic intrusive bedrock. The Baker Zone is located approximately 1 km northeast of the Lac Des Iles Roby pit. Glacial striations indicate the last ice flow direction was 240°. Two sampling lines parallel to ice flow direction extended 425 m down-ice and 200 m up-ice from known mineralization. The terrain is predominantly bedrock covered by a thin layer of till. The number of each sample media collected at the Baker Zone are: 36 B-horizon soil; 45 C-horizon till for fine fraction (-63µ) geochemical analysis and 11 C-horizon till for HMC analysis.

Lac Des Iles – Powerhouse Zone

The Powerhouse Zone is located approximately 0.5 km southwest of the Lac Des Iles Roby Pit. This area has little exposed bedrock due to a cover of glacial drift. Numerous boulders are located on surface in some areas. The underlying bedrock geology is not well known due to the poor exposure. Samples taken in this area extend 2500 m down-ice from the Roby Pit at 200 m intervals along 3 transect lines. For the period of 1994 to 1999 the Roby Pit has produced 393 428 oz of palladium and 26 669 oz of platinum (North American Palladium Ltd's http://www.napalladium.ca). A breccia zone within a mafic to ultramafic intrusive complex is host to the PGE ore (North American Palladium Ltd's http://www.napalladium.ca). The number of samples collected on the Powerhouse Zone for each sample media are: 20 B-horizon soil; 21 C-horizon till for fine fraction (-63μ) geochemical analysis and 21 C-horizon till for HMC analysis.

Le Gris Lake

Avalon Ventures Ltd. and Starcore Resources Ltd. joint venture Le Gris Lake Property is located approximately 8 km southeast of the Lac Des Iles Mine. Two sample lines established parallel to the last ice flow direction of 220° traversed mineralization of greater than 300 ppb PGE within the ultramafic complex (J.C. Pederson, Avalon Ventures Ltd., personal communication, 2000). Samples were spaced at 25 m intervals along lines that extended 200 m down-ice and 175 m up-ice from the mineralization. The number of each sample media collected on the Le Gris Lake Property are: 32 humus; 30 B-horizon soil; 27 C-horizon till for fine fraction (-63μ) geochemical analysis and 8 C-horizon till for HMC analysis.

Wolf Mountain

The Wolf Mountain Property is located approximately 65 km north of Thunder Bay and is jointly controlled by Avalon Ventures Ltd., East West Resources Corporation and Canadian Golden Dragon Resources Ltd. The bedrock on the Wolf Mountain property is unique in that the ultramafic bedrock has weathered in place to form a regolith. Overburden samples were collected from surficial trenches located within 1 km of bedrock that had been sampled by the company during 1997. Results from the 1997 bedrock sampling returned values as high as 7.66 g/t of combined Pt and Pd (Avalon, East West and Dragon, News Release, July 27, 2000). The number of each sample media collected on the Wolf Mountain Property are: 4 humus; 11 B-horizon soil; 6 C-horizon till for fine fraction (-63μ) geochemical analysis; 2 C-horizon till for HMC analysis and 12 vegetation.

METHODOLOGY

Overburden samples were collected from road cuts, trench exposures or hand dug test pits of approximately 1 m in depth. Humus samples, collected for geochemical analysis, were sieved at the sample site to remove any undecomposed debris such as roots. Humus samples will be processed and the less than 177 μ size fraction will be analyzed at MNDM's Geoscience Laboratories. B and C-horizon samples, the fine fraction (-63μ,) component of which will undergo geochemical analysis, will also be analyzed at the Geoscience Laboratories. Bulk C-horizon till samples of 10 kg were collected at some sites. These samples were sieved at the sample site using a number 4 (0.5 mm mesh) screen. The heavy mineral concentrate (HMC) derived from the sand size fraction (0.25 to 2 mm) will be visually analyzed for indicator minerals that are associated with PGEs, gold, kimberlite and base metals, as well as the MMSIM® suite. The HMC will also undergo geochemical analysis. Pebbles removed from the sample by the number 4 mesh screen were collected and stored for lithologic description. The outer bark of black spruce trees was collected for geochemical analysis.

PROJECT STATUS

Sample collection for this project took place during the period of July to September 2000 during which time 242 sites were sampled. The total number of samples collected for each medium are: 144 humus; 194 B-horizon soil; 163 C-horizon till for -63μ fraction analysis; 77 C-horizon till for heavy mineral concentrate; 77 for pebble lithologic description and 24 vegetation. All samples have been submitted for laboratory analysis. An Open File Report and data release, expected to be available in early 2001, will provide sample locations and results.

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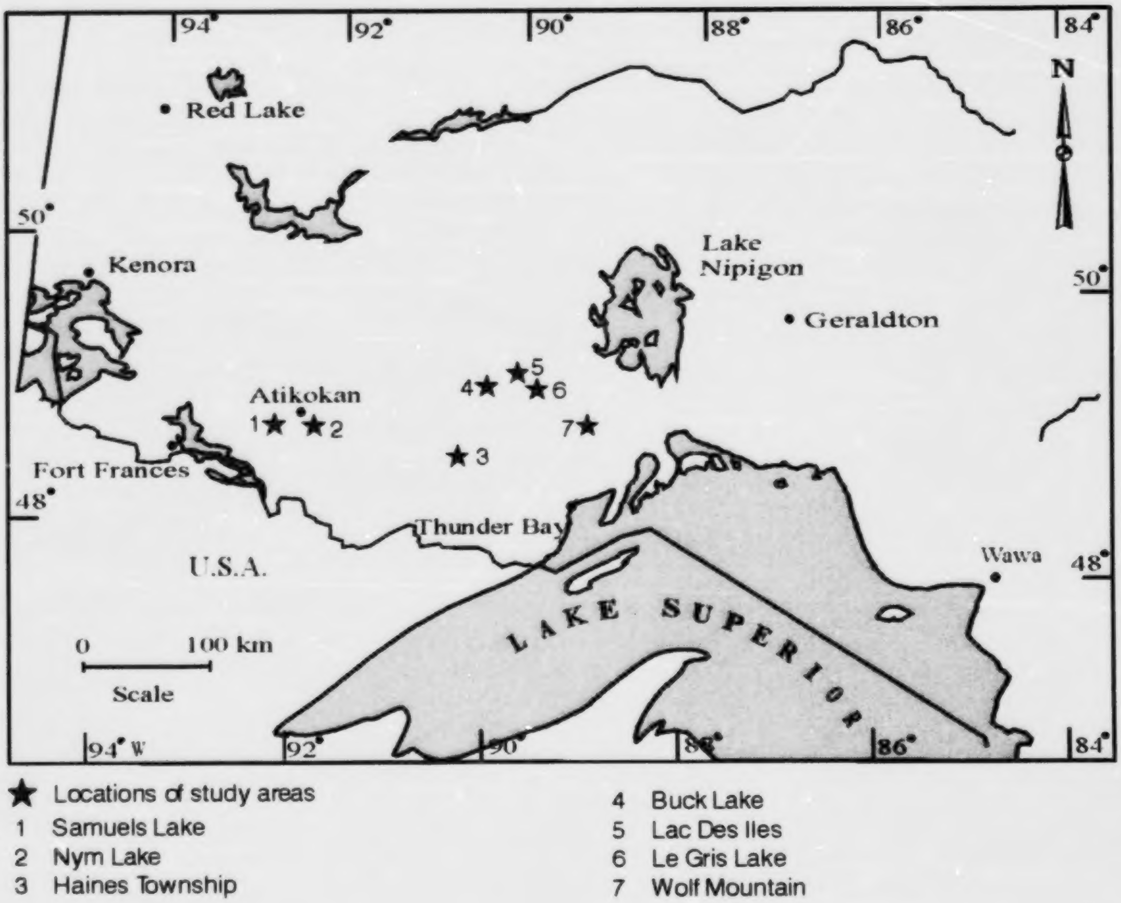

Figure 35.1 Locations of study areas

36. Project Unit 00-35. Kabinakagami Lake Area High Density Regional Lake Sediment and Water Geochemical Survey, Northeastern Ontario

J.E. Jackson[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

A helicopter supported regional lake sediment and water geochemical survey of the Kabinakagami Lake area was conducted by Sedimentary Geoscience staff from June 15 to July 5, 2000. Kabinakagami Lake is located about 100 km northeast of Wawa, Ontario. The survey covered the western portion of the Kabinakagami Lake greenstone belt located between Hornepayne and White River, Ontario (Figure 36.1). The eastern portion of the greenstone belt from Walls Township to Champlain Township has been sampled by a recently completed Operation Treasure Hunt geochemical program (Ontario Geological Survey 2000). Lake and water samples were collected from a 3700 km^2 region that wholly encompasses the area represented on National Topographic System map sheet 42 C/16 and portions of NTS sheets 42 F/1, 42 F/2, 42 C/9, 42 C/10 and 42 C/15. Lake sediment and/or water samples were collected at 1035 sites for an average density of 1 sample per 3.5 km^2. The Kabinakagami Lake survey is part of a 2 year project to sample the Kabinakagami and the Dayohessarah greenstone belts.

BEDROCK GEOLOGY

The Kabinakagami greenstone belt is part of the Wawa Subprovince and forms an arcuate assemblage of dominantly mafic metavolcanic rocks with subordinate metasedimentary rocks and sparse occurrences of intermediate to felsic metavolcanic rocks (Williams et al. 1991). The greenstone belt is approximately 100 km long and extends from Champlain Township in the east to Nameigos Township in the west. The belt ranges from 1 to 6 km wide with the widest section occurring in the Kabinakagami Lake area (Wilson 1993). The supracrustal rocks are strongly sheared, steeply dipping and range from upper greenschist to middle amphibolite grade (Wilson 1989).

The Puskuta Lake shear zone separates the east to southeast trending northern portion of the greenstone belt from the northeast trending southern portion of the belt. The shear zone is at least 60 km long, 1 to 2 km wide and is characterised by intense ductile deformation followed by an episode of brittle faulting (Leclair 1990). The northern part of the greenstone belt in Hawkins and Walls townships contains highly deformed metavolcanic rocks, rare metasedimentary rocks and numerous quartz-feldspar dikes and sills (Wilson 1990). In the Kabinakagami Lake area the supracrustal units contain more metasedimentary rocks, less prominent quartz-feldspar dikes and sills and moderate shearing and deformation. The main structures in the southern part of the belt are a northeast trending syncline with the axis trending under Kabinakagami Lake and the northeast trending Bear Creek fault zone (Siragusa 1977). The Bear Creek fault is a zone of high strain from 50 to 100 m wide located to the northwest of the Hiawatha gold mine. The fault zone contains numerous, narrow, parallel shear zones with silica and chlorite alteration. The high strain zone of the Bear Creek fault hosts all of the known gold occurrences in the Lizar Township area (Wilson 1993).

The greatest economic mineral potential of the Kabinakagami greenstone belt is related to gold mineralization. Gold mineralization is found in both local and regional shear zones within deformed metavolcanic and felsic intrusive rocks. Silica and chlorite alteration is common in the Kabinakagami Lake area while silica and carbonate alteration is prominent along the Puskuta Lake shear zone. Historical gold production in the Kabinakagami greenstone belt is known from the Shenango and Hiawatha gold mines. Both mines were low grade and tonnage operations. The Hiawatha gold mine is located in Lizar Township adjacent to the Bear Creek fault zone and the Shenango gold mine occurs in the Puskuta Lake shear zone in Hawkins Township.

PHYSIOGRAPHY AND QUATERNARY GEOLOGY

Most of the topography in the area is of moderate relief with much of the terrain being bedrock controlled (Gartner and McQuay 1980). The northern portion of the survey area is a dominantly flat, swampy terrain with elevations ranging from 320 to 350 m above sea level. The terrain is more rugged in the southern portion of the survey area with elevations ranging from 396 to 500 m above sea level (Siragusa 1978). Numerous, small, narrow lakes in the southern portion of the area occupy valleys along dominant northeast and northwest trending structures in the granitic basement rocks.

A regional compilation of the Quaternary geology (Barnett et al. 1991) indicates, that most of the bedrock in the southern portion of the study area is covered by a thin veneer of discontinuous glacial drift. Quaternary deposits cover much of the bedrock in the northern part of study area and consist predominantly of silty to sandy till with some carbonate-rich clays (Siragusa 1977, 1978). Glaciofluvial outwash and ice-contact deposits are the dominant landforms in the northern part of the survey area. In general, the outwash is sandy and occurs as a thin veneer over bedrock (Gartner and McQuay 1980). Esker deposits generally trend in a south to southwesterly direction and are composed mainly of sand with some gravel. The largest esker in the area extends for about 20 km along the eastern shore of Kabinakagami Lake. Glaciolacustrine sand, silt and clay occur in scattered locations throughout the map area. These sediments were deposited in Glacial Lake Barlow-Ojibway (Gartner and McQuay 1980).

SAMPLING METHODS

Where possible, organic lake sediment and water samples were collected at each lake site. If a site contained no organic component (e.g., sand and/or clay), then, only a water sample was taken. The organic sediment was collected in a gravity corer that was lowered from the helicopter float; the sediment was then pulled to surface and deposited into a sample bag. The upper 20 cm of the sample was discarded to avoid anthropogenic bias in the geochemical data and to avoid water/sediment interface effects (i.e., increased Mn due to anoxic conditions that result in secondary accumulation of base metals). The sediment below the 20 cm depth better reflects the natural element abundance that may be attributed to the local geology (Dyer 1999). Each sample was then sealed in an airtight plastic bag in order to avoid contamination between samples.

A submersible pump was lowered into the lake to collect the water samples. The pump would flush for about 10 seconds (to avoid contamination from a previous lake) and then fill a sample bottle along with the flow cell on the YSI conductivity/pH probe. The depth the water samples were collected at varied from near surface (for lakes <1 m deep), to 1 m (for lakes 1-3 m deep) to 3 m for deeper water bodies. The water samples were kept cool and processed (filtered and acidified) when the crew returned to base camp.

At each site, sediment descriptions and observations were logged into a database on a pen based notebook computer. The pH, temperature, conductivity, oxidation-reduction potential and dissolved oxygen of the water samples was recorded on the YSI probe and a GPS waypoint for the sample sites was taken.

SAMPLE PREPARATION AND ANALYTICAL PROGRAM

The organic lake sediments were placed in a breathable fabric sample bag and partially air dried in base camp prior to shipment to the laboratory. The samples are freeze dried to retain any volatile elements, partially pulverized and sieved to attain a –80 mesh size fraction. Laboratory analysis of the –80 mesh fraction of the organic sediments will include nitric-aqua regia digestion followed by inductively coupled plasma-mass spectrometry (ICP-MS) to determine about 50 trace elements. The nitric acid-aqua regia digestion technique attacks all the matrix constituents in the sample except for the silicate minerals and is therefore considered a nonselective, relatively strong partial extractant (Dyer 1999).

For each sample, about 15 g of prepared material will be pressed into briquettes and submitted for analysis by instrumental neutron activation. Duplicates of samples and certified reference materials will be used to monitor the quality control of all analyses. Loss on ignition is determined at 500 °C, using an automated gravimetric technique.

The water samples were filtered through a 0.45 µm syringe held filter and acidified to 1% ultrapure nitric acid within 24 hours of collection. Direct aspiration ICP-MS will be used on the water samples to analyze for approximately 50 elements including major cation and anion species. Sample duplicates, blanks and certified reference standard SLRS-4 will be used to monitor the quality control of the water analyses.

PRELIMINARY RESULTS

The average electrical conductivity (EC) for surface waters sampled from the survey is 121.9 µS/cm with samples ranging from <10 to 406 µS/cm. Figure 36.2 illustrates the range of EC values across the study area. The average EC conductivity value for the supracrustal assemblages is slightly higher at 138 µS/cm than the average value for the surrounding granitoid rocks at 119 µS/cm. Some of the higher EC values occur in lakes over glaciofluvial deposits.

The pH of the surface waters ranged from 5.5 to 8.9 with an average pH of 7.8. The pH of surface waters for the study area is shown on Figure 36.3 plotted with major surficial Quaternary deposits. The pH of lake waters shows a regional trend of neutral to slightly acidic values in the southern portion of the map area and slightly more alkaline values in the northern portion of the area. This is likely due to a thicker Quaternary drift cover in the northern part of the survey area. Some of the higher pH (alkaline) values and higher EC values occur in lakes underlain by glaciofluvial deposits and may indicate the presence of dissolved carbonate minerals in the water.

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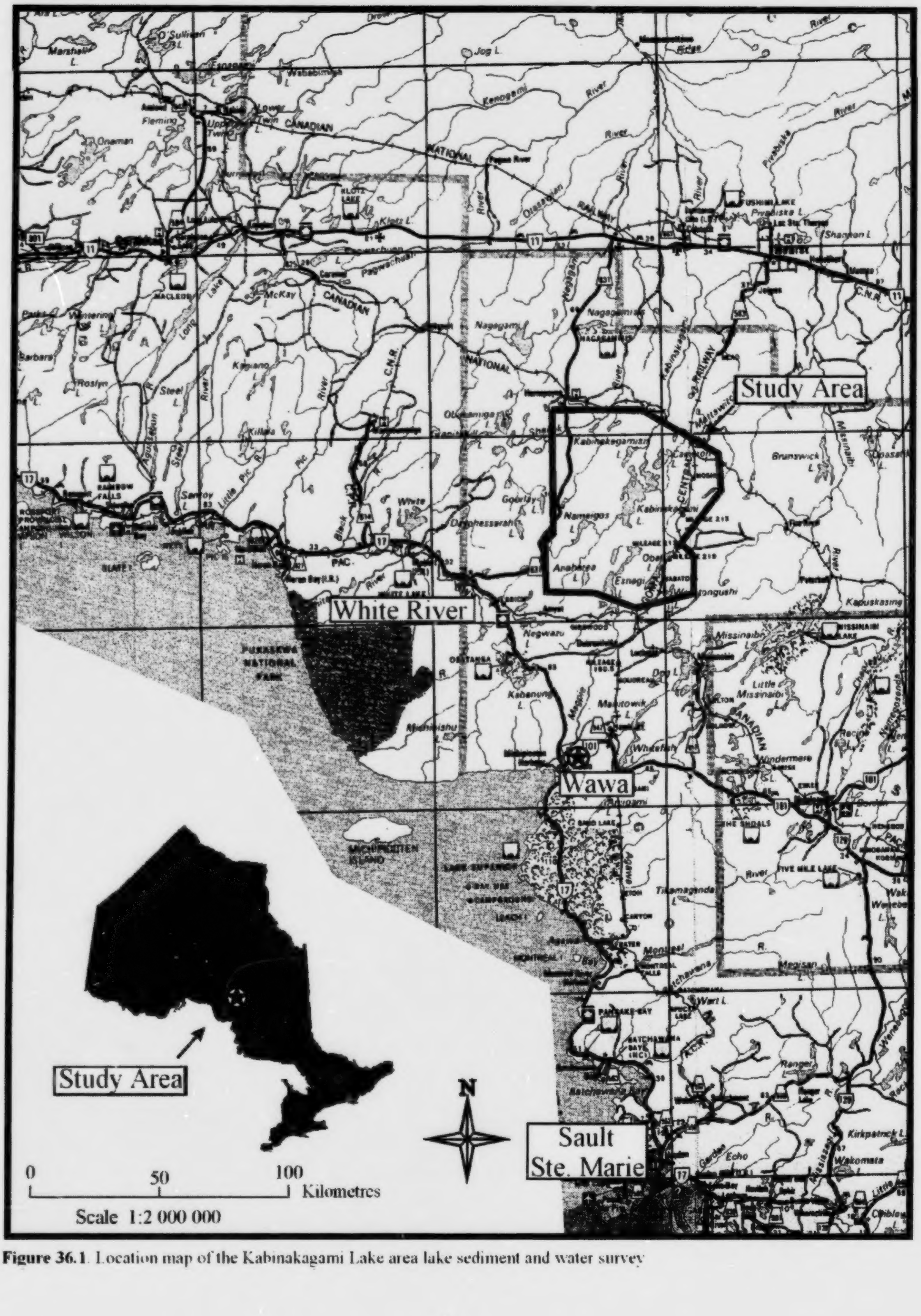

Figure 36.1. Location map of the Kabinakagami Lake area lake sediment and water survey

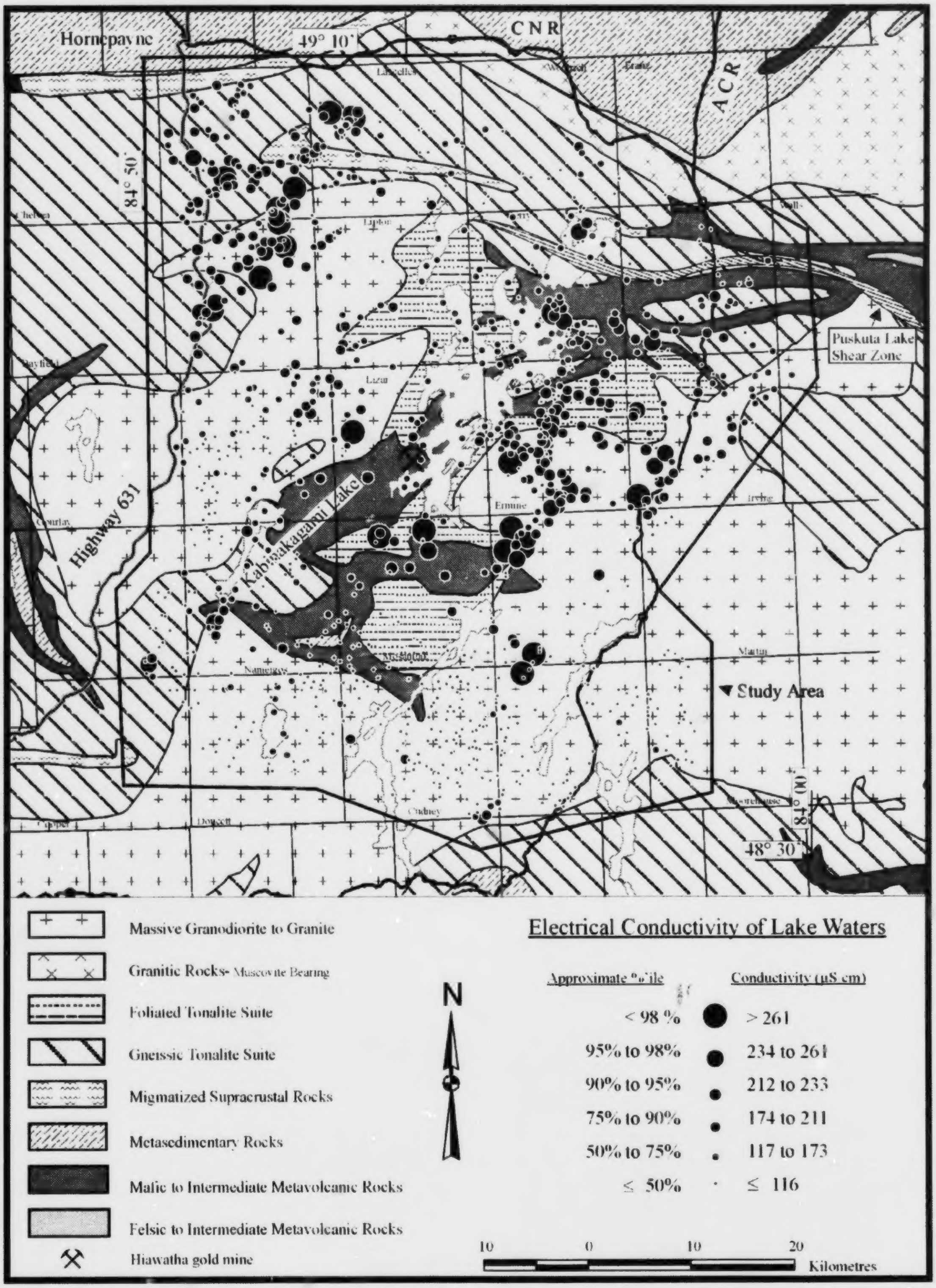

Figure 36.2. Electrical Conductivity of lake waters and bedrock geology (after Ontario Geological Survey 1991)

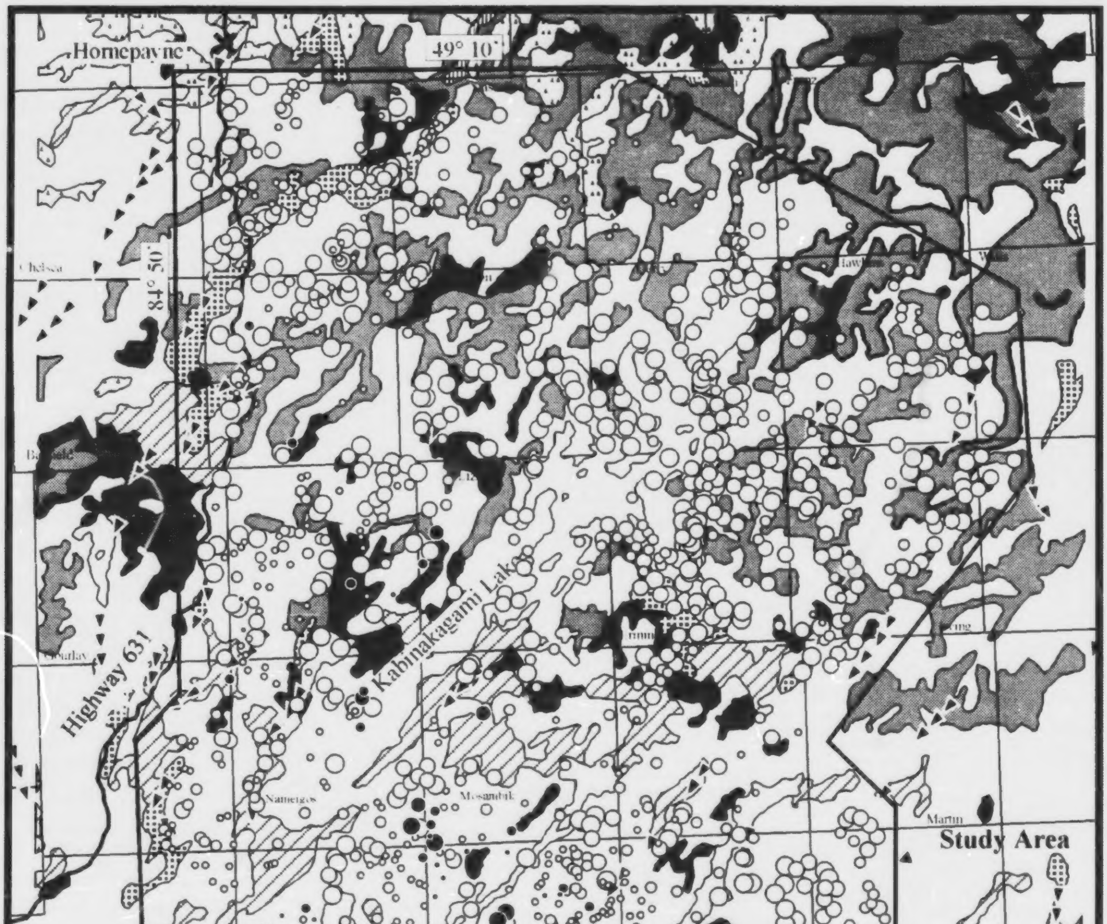

Figure 36.3. Lake water pH and Quaternary geology (after Barnett et al. 1991)

37. Project Unit 00-039. Savant Lake High Density Regional Lake Sediment and Water Geochemical Survey, Northwestern Ontario

D.F. Russell[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Fieldwork for a high-density lake sediment and water geochemical survey for the Savant Lake area was carried out from July 17 to August 5, 2000. The survey area is located approximately 300 km north-northwest of Thunder Bay, and covers portions of the area defined by National Topographic System (NTS) 1:50 000 scale map sheets 52J/6, 52J/7, 52J/8, 52J/9 and 52J/10 (Figure 37.1). Lake sediment and/or water samples were collected at 1186 sites, giving an average density of 1 sample per 2.2 km^2.

The Savant Lake area was selected for this type of survey for reasons including client interest, mineral potential of the area and minimal coverage of geochemical exploration data for the region. The nearest area for which a regional lake sediment data set has been produced is significantly south of the study area. This data was collected through the national geochemical reconnaissance (NGR) lake sediment program undertaken by the Geological Survey of Canada in the 1970s. As a result, the current program will provide new regional geochemical data at a relatively high resolution.

BEDROCK GEOLOGY

The most recent and complete bedrock mapping and compilation for the study area was completed by Trowell (1986). Much of the Savant Lake Area has been previously mapped by Bond (1977, 1979, 1980). Trowell (1981) mapped the Beckington Lake Area, and Trusler (1982) mapped the Farrington Lake Area in the western part of the survey area. More recent work has focussed on a re-examination of the structure and stratigraphy of the region in order to determine how the deformation events have affected volcanogenic massive sulphide (VMS) and precious metal mineralization (Sanborn-Barrie 1990).

The Savant Lake greenstone belt strikes east-northeast for about 80 km from the Marchington River in the west to the Flindt River in the east. It varies considerably in width, from 2 km in the west to over 25 km in the eastern portion. The area is divided into 3 primary units: the Jutten volcanic group (JVG), the Savant sedimentary group (SSG) and the Handy Lake volcanic group (HLVG). The Kashaweogama Lake fault extends westerly through the area and cuts all of the units.

The JVG, the lowermost unit of the Savant Lake greenstone belt, occurs in the northern and eastern parts of the study area. It consists of mafic flows of pillowed and massive Fe/Mg tholeiites and komatiitic basalts, minor ultramafics and chert-magnetite ironstone (Sanborn-Barrie 1990; Blackburn et al. 1991). These metavolcanic rocks are overlain unconformably by the SSG and the HLVG, which occupy the central and western portions of the Savant Lake greenstone belt. The SSG is composed of feldspathic and lithic wacke interbedded with magnetite-chert ironstone. Its base is defined by the Savant Narrows

Formation, a polymictic clast- to matrix-supported conglomerate that grades into the felsic and intermediate pyroclastic flows of the Whimbrel Lake Formation (Trowell 1986). This group extends along the length of the Kashaweogama Lake fault. The HLVG makes up most of the western part of the Savant Lake greenstone belt. This group comprises intermediate to felsic pyroclastic rocks and flows, including tuff and lapilli-tuff (Bond 1980).

Previous exploration efforts in the area include discoveries of gold in 1926 and 1940 in the area of Savant Lake (Bond 1977). In 1968, the Zn-Cu-Ag-Pb Mattabi Mine was discovered on Sturgeon Lake, south of the present survey area. This led to a dramatic increase in the exploration for base metals in the late 1960s and 1970s, particularly within the HLVG which shows similarities to the South Sturgeon Lake volcanics (Trowell et al. 1980).

PHYSIOGRAPHY AND QUATERNARY GEOLOGY

The Savant Lake area is characterised by gentle topography with local relief rarely in excess of 75 m. Engineering geology terrain maps were produced for the area at a scale of 1:100 000 (Gorman 1989a, 1989b; VanDine 1989a, 1989b). These maps indicate that the area is covered by discontinuous glacial drift consisting of sandy till deposits, sand/gravel eskers and small organic peat deposits. The area between Savant, Armit and Miniss lakes is predominantly exposed bedrock or bedrock covered by a thin layer of sandy till. Northeast of this area, ground cover is mostly till, with localized esker deposits and exposed bedrock. To the southwest, the amount of esker material increases while exposed bedrock decreases. These eskers vary in size, reaching up to 25 km in length and 2 km in width. The regional orientation of these glaciofluvial systems is to the northeast, corresponding with the direction of glacial retreat in the area.

River valleys cut through pre-existing glacial drift and are filled with modern alluvial deposits of silt and sand.

SAMPLING METHODS

Sampling of organic lake sediments was performed by 2-person teams using a float-equipped helicopter. Overall, an average of 17 lakes were sampled for each hour of helicopter time. The samples were collected using a gravity corer designed by the Ontario Geological Survey. Samples were taken from depths >20 cm below the sediment/water interface (SWI) in order to minimise or avoid anthropogenic influences and SWI effects. These deeper sediments more accurately reflect the geochemical effects that may be traced back to local bedrock geology (Dyer 1998). The samples were extruded from the collection tube into breathable fabric bags and then placed in a sealable plastic bag until the end of the sampling run.

Lake water samples were taken simultaneously with the sediment samples. On lakes <3 m deep, water samples were collected at a depth of 0.5 m below the water surface while on lakes deeper than 3 m samples were collected at a depth of 2 m. A semi-automated water sampling apparatus, developed by the OGS, was used for the collection of samples. The apparatus consists of a submersible pump, a water quality meter (for measurement of parameters such as pH, temperature and conductivity), a sample bottle tray and a variety of hoses and valves. Water from the lake was pumped through the system in order to purge it prior to the collection of a sample and the recording of water quality data. The water samples were kept cool immediately following collection and were processed (filtered and acidified) upon return to base camp at the end of the sampling run.

Sample site locations were recorded using a GPS receiver mounted in the cockpit of the helicopter. A customised database application operating from a pen-based computer was used to record the sediment sample information and descriptions, while the water quality data was recorded using the YSI data logger and then transferred to the computer system at the end of each sampling run.

SAMPLE PREPARATION AND ANALYTICAL METHODS

While in the field, lake sediment samples were placed in porous collection bags and partially air dried. Upon arrival at the laboratory, the samples were fully dried, partially pulverised in a ceramic ring mill and subsequently sieved to obtain the -80 mesh (<177μm) size fraction. Laboratory analysis will include nitric-aqua regia digestion followed by inductively coupled plasma-mass spectrometry (ICP-MS) for the determination of approximately 50 trace elements. Nitric-aqua regia digestion attacks all sample matrix constituents except for silicate minerals, and therefore is considered a non-selective, relatively strong partial extractant (Dyer 1998).

Approximately 15 g of sample pulp will be pressed into briquettes prior to analysis by instrumental neutron activation analysis (INAA). Quality control will be monitored through the use of sample pulp duplicates and certified reference materials. Loss on ignition (LOI) is determined at 500°C using an automated gravimetric technique.

Water samples were passed through 0.45 μm syringe filters and acidified to 1% ultrapure nitric acid within 24 hours of collection. Analysis of water will include direct aspiration inductively coupled plasma-mass spectrometry (ICP-MS) to determine approximately 50 elements including major cation and anion species. Quality of the analyses will be monitored through the use of sample duplicates, certified reference standard SLRS-4 and blanks (distilled water).

PRELIMINARY RESULTS

The pH for lake waters in the survey area (Figure 37.2) ranges from 4.30 to 8.91 with an average of 7.08. Two regional trends in pH are evident in the survey area. First, in areas of thin or no overburden, determined from VanDine (1989a, 1989b) and Gorman (1989a, 1989b), the pH values tend to reflect the underlying geology. The pH values for metavolcanic rocks are more alkaline relative to the values in granitoid rocks which tend to be slightly acidic. This may be partially due to carbonatization within the greenstone belt as a result of intense folding and hydrothermal alteration. Second, the study area shows a shift from more alkaline conditions in the northeast to slightly acidic in the southwest. This trend is likely the result of a decrease in the carbonate content of glaciofluvial and ground moraine deposits in this direction, and may also mask the bedrock effects in many areas.

Electrical conductivity (EC) values (Figure 37.3) vary between <10 μS/cm and 245 μS/cm, averaging 47.3 μS/cm. These values tend to mirror the trends for pH, and appear to be strongly affected by the nature of the underlying material. Higher EC values are related to glaciofluvial deposits throughout the area, till deposits in the northeast, and metavolcanic units in areas of thin or no overburden. Lower EC values tend to be associated with exposed areas of granitoid plutonic rocks. The higher values most likely reflect the presence of dissolved carbonate minerals derived from the glacial deposits as well as hydrothermal alteration of the greenstone bedrock. They may also indicate the occurrence of weathered sulphide minerals derived from either bedrock or surficial deposits.

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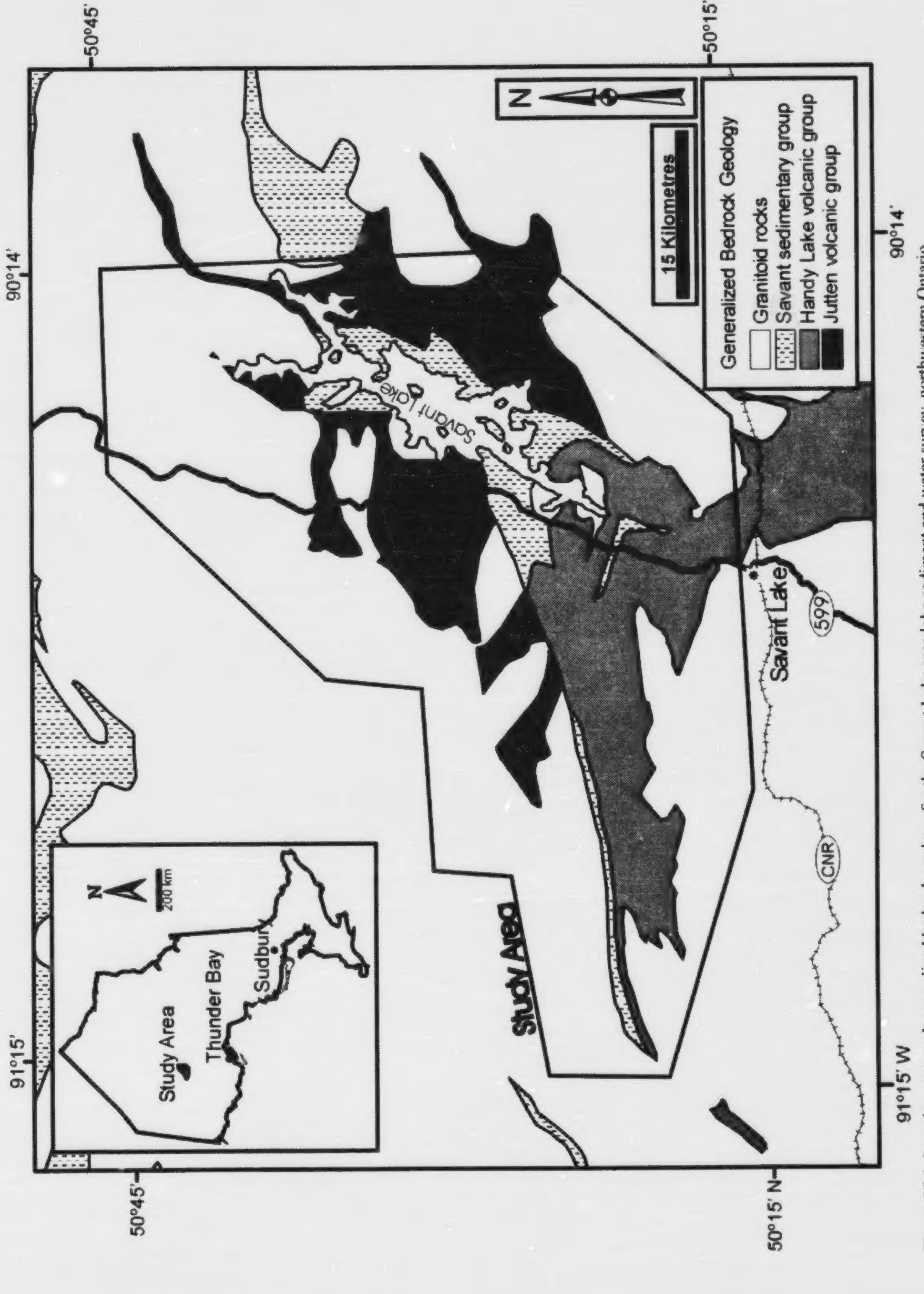

Figure 37.1. Location map and generalized bedrock geology for the Savant Lake area lake sediment and water survey, northwestern Ontario. Geology after Ontario Geological Survey (1991) and Blackburn et al. (1991).

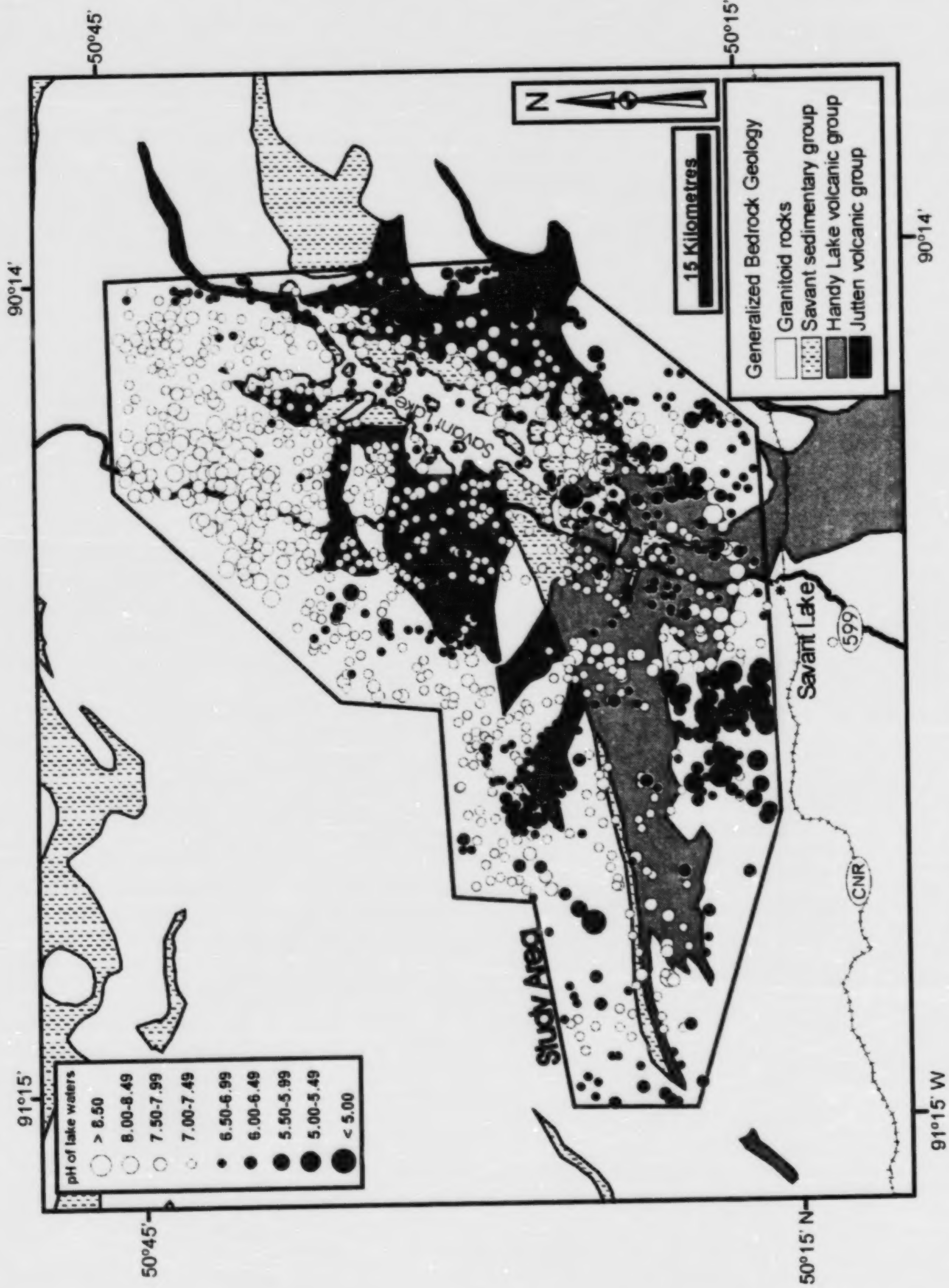

Figure 37.2 Generalized bedrock geology and pH in lake waters

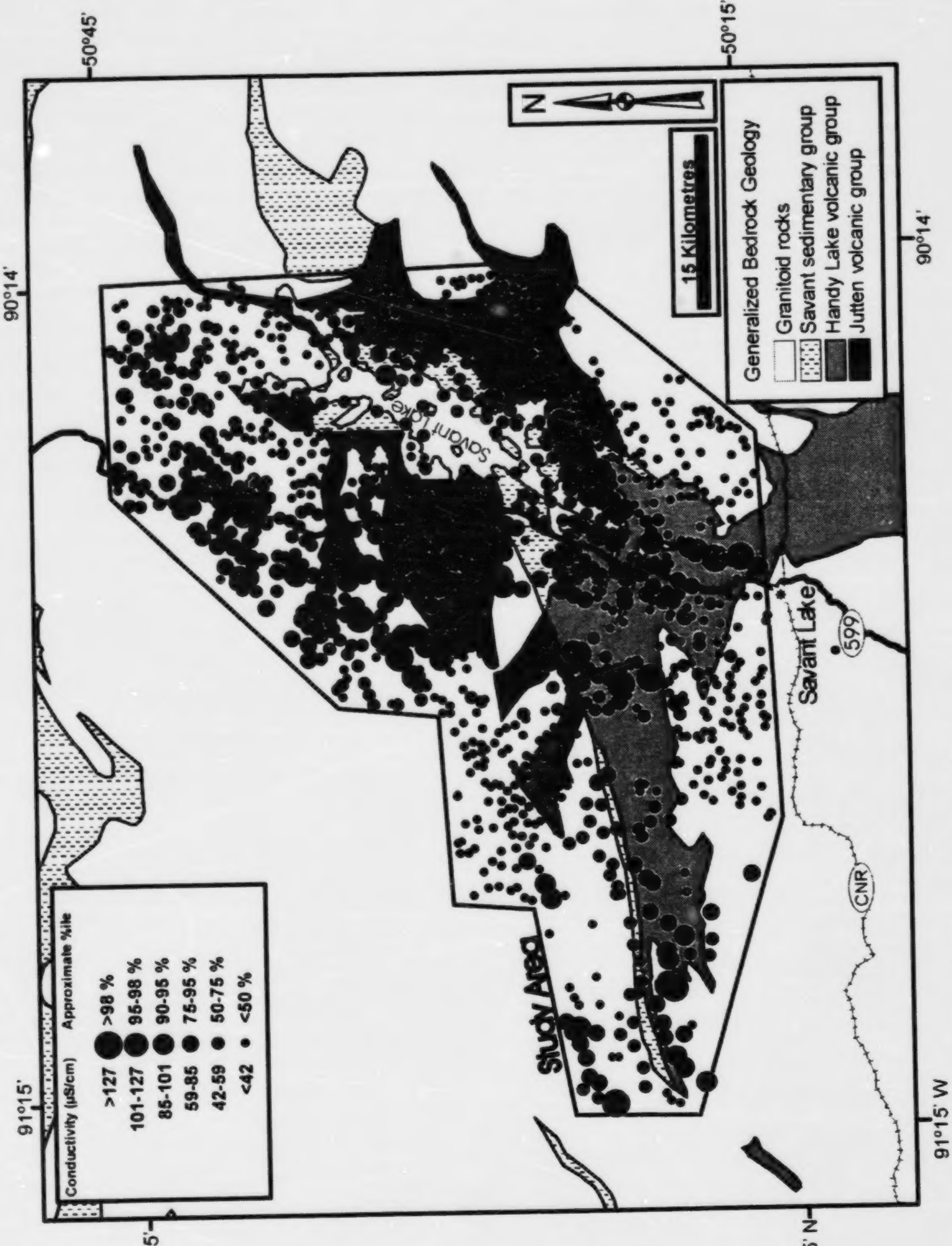

Figure 37.3 Generalized bedrock geology and electrical conductivity in lake waters

38. Project Unit 00-033. Satellite-based Engineering Geology Terrain Studies for Ontario's Far-North

P.J. Barnett[1] and V.H. Singhroy[2]

[1]Sedimentary Geoscience Section, Ontario Geological Survey
[2]Canada Centre for Remote Sensing, Natural Resources Canada

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INTRODUCTION

Approximately 20 years ago Northern Ontario Engineering Geology Terrain Studies (NOEGTS) were completed for that part of the Canadian boreal forest region lying south of latitude 51° N (Gartner et.al. 1981). Each study included a 1:100,000-scale terrain map that was based almost entirely on the interpretation of air photographs with limited field checking. The map legend contains information on surface material type, landform, topography (relief) and drainage condition.

The NOEGTS terrain maps produced previously have been quite useful in providing regional information on geological conditions of the landscape. These conditions affect or determine resource capability of an area as well as identify and outline possible constraints (Gartner et.al. 1981). They have been used extensively for regional planning purposes in forest management, drift exploration and in ecological land classification studies by both private and public organizations. The area north of 51° N latitude is in need of such terrain information. It is a part of Ontario's new frontier for the mineral and forest industries.

NOEGTS maps would be expensive to create in the traditional manner because of the vast area to be covered, limited access and ground truthing that would be required. The 2-year joint Ontario Geological Survey and Canada Centre for Remote Sensing (OGS-CCRS) project, described herein, attempts to undertake pilot studies designed to create terrain maps using the integration and interpretation of various types of remotely sensed imagery, digital elevation models, their derivatives and geological depositional models.

It is suggested that information on the various legend components: material, landform, topography and drainage, can be derived from the interpretation of digital elevation models (DEM), their derivatives and remotely sensed imagery through the use of established landform/sediment models. The DEM and derivatives, such as hill-shaded DEM, slope, and elevation range models, in conjunction with LANDSAT 7, RADARSAT, and high resolution satellite imagery, are being used in several pilot areas to determine if image-based terrain maps can be created portraying similar information to that of the NOEGTS maps. Six (6) pilot areas were chosen from within the area of Ontario's boreal forest bounded by Latitudes 51° and 54° N and Longitude 87° W and the Manitoba border (Figure 38.1).

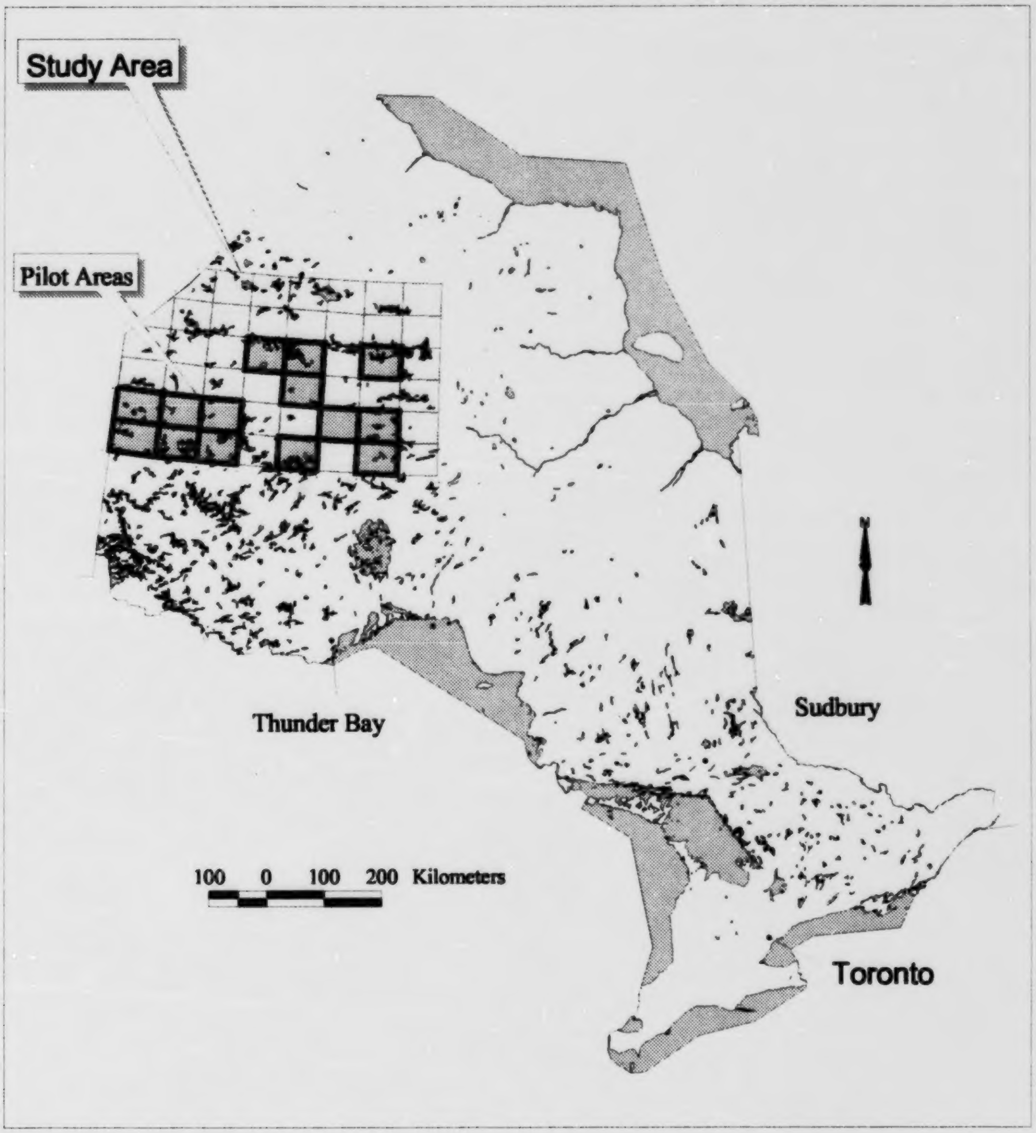

Figure 38.1: Location of the study area and areas being considered for pilot projects in northwestern Ontario.

PROGRESS TO DATE

The project began in April, 2000 and to date, emphasis has been placed on data collection, data processing and methods development. Data collection and processing included the construction of hydrologically-conditioned digital elevation models (DEMs) of the entire study area. Created by the Geomatics Service Centre (Ministry of Natural Resources, Peterborough) for this project, the DEMs were generated using elevation information, the drainage network and water polygons in the interpolation process. This process creates a higher quality representation of the land surface as a result of incorporating drainage enforcement into the DEM algorithm. The DEMs were processed for the entire area in 4 batches and the individual 1:100 000 scale tiles of the 47 areas subsequently clipped out. In addition, the Geomatics Service Centre prepared hill-shaded DEM coverages (ArcInfo™) for all 47 tiles.

Several types of remotely sensed data have also been acquired for use in this project. Complete RADARSAT data coverage is currently being assembled and Landsat 7 Extended Thematic Mapper (ETM) multispectral and panchromatic data is being acquired for the entire study area. Two scenes of IRS-1-C imagery were purchased for the Trout Lake and Pikangikum pilot project areas. Processing of the remotely-sensed imagery is underway for all of the pilot project areas.

This past summer, methodology work concentrated on the Trout Lake and Pikangikum pilot project areas located approximately 550 km northwest of Thunder Bay. The communities of Red Lake, Balmertown, Cochenour and Pikangikum lie within these areas. Most of the work has been concentrated in the Trout Lake area with the goal to produce a prototype map for this area by November (Barnett et al. in press).

PRELIMINARY FINDINGS

The Trout Lake and Pikangikum areas are characterized by irregular bedrock-dominated terrain underlain by Precambrian igneous and metamorphic rocks (Canadian Shield). The area was last glaciated during the Wisconsinan Stage by the Nouveau Québec Sector of the Laurentide Ice Sheet. During deglaciation of the area, a large, ice-contact glacier-fed lake fronted the ice margin (glacial Lake Agassiz). The interactions of the glacier with the glacial lake controlled depositional environments and, hence, the distribution and types of landforms, origin (glacial, glaciofluvial or glaciolacustrine), material types and sediment distribution.

Direct glacial sedimentation was deposited primarily under the glacier (till) or along the ice margin or grounding line (flowtills). Subglacial landforms include till plains and fluted till plains, drumlins and eskers. Ice-marginal landforms include one large end moraine, the Lac Seul Moraine (Prest 1963) which contains deltas and subaqueous fans, and grounding line fans commonly referred to as DeGeer moraines. The Lac Seul Moraine is considered by some to be a very large grounding line fan produced during a catastrophic release of stored meltwater within the Laurentide Ice Sheet (Sharpe and Cowan 1990).

Sedimentation into the glacial lake was dominated by density underflows as a result of density differences between the incoming sediment-charged meltwater and the lake water. In this setting, the distribution of fine-grained sediments is controlled by lake-bottom topography and elevation, with sediments being preferentially deposited in topographically low areas. Abandoned shoreline features, beaches, bars and spits, of glacial Lake Agassiz are well developed along the Lac Seul Moraine and other isolated hills of ice-contact sediments. Several levels of this lake are recorded. Wave and current action in this lake has also produced large areas of bedrock outcrop, washed clean of any pre-existing glacial sediment. Many small wetlands occur in bedrock-dominated terrain and in areas of low relief, grounding line fans. Larger areas of wetlands occur within the broad plains underlain by glaciolacustrine fine-grained sediments.

With the above depositional models and landscape conditions in mind, the methodology developed included the direct interpetation of the DEMs, as well as several derived products that were created to aid in the interpretation of landform, material-type, relief and drainage conditions. These included the hill-shaded DEMs, slope, aspect, and elevation range models. These derived products were produced using

ArcInfo™ and ArcView™ software packages. Landsat 7 Extended Thematic Mapper (ETM) multispectral and panchromatic data, IRS-1C panchromatic and RADARSAT data were also used in the interpretation. Initial geological analysis was based on individual image maps of one degree of longitude and one-half degree of latitude. Image maps were created using each of the 4 sensor types. A method was then devised to combine the sensors with the hill-shaded DEM data, and image maps of combined products (ETM multispectral + DEM, ETM panchromatic + DEM, IRS 1-C panchromatic + DEM, RADARSAT SAR + DEM), were also created (Singhroy et al. in press). The color or black and white image maps were printed at a scale of 1:100 000. The maps were used in the field and interpreted visually by integrating the field information.

Field visits to the Trout Lake and Pikangikum areas were undertaken during the summer of 2000. Observations on material type, forest cover and terrain conditions were made at selected sites as ground truth for image interpretation. Material relationships were observed at some sites and appropriate geologic models identified and refined.

Analysis of the DEM, the derived hill-shade, slope and aspect maps aid in mapping the various landscape elements. The hill-shaded DEM provides a general overview of the terrain. Areas of glacial and glaciolacustrine sedimentation occur as smooth areas on this image and rock-dominated terrain have a very irregular appearance. The Lac Seul Moraine, for example, stands out as a dominant, linear topographic high. On the slope map, the moraine has steep slopes on the proximal side and gentler slopes on the distal side. Ice-marginal deltas and subaqueous fans have their own characteristic shape but slope relationships are similar to that of the end moraine. The granular nature of the materials associated with these landforms (predominantly ice-contact stratified sediments) and their positive relief makes these sites very well drained and allows them to support the growth of jack pine (*Pinus banksiana*).

Glaciolacustrine sediments and subglacially-deposited till form plains which are recognizable on the DEM and slope maps. Plains of lower elevation tend to be underlain by glaciolacustrine materials and plains at higher elevations are commonly underlain by till. Only a few of the larger, generally low-relief, linear grounding line fans are recognizable on the DEM, however, these forms can be seen as promontories and/or linear islands within the area lakes and as linear tonal variations on the ETM and IRS images.

Areas of irregular topography and short complex slopes are either bedrock-dominated areas or stagnant ice deposits (small fans and kettles). Separation of these 2 area types, as well as several of the others discussed above, can be done in association with the remotely sensed images based on forest variability.

The relief component of the legend can be derived using a 30x30 pixel filtering technique of the range in elevation values in the DEM. The resultant data can then be classed into the low (<15 m), moderate (>15 m to <60 m) and high (>60 m) relief classes used in the NOEGTS maps.

The main components of the NOEGTS maps legend are material type, landform, topography and drainage condition. Information on landform and topography and inferences to material type, based on landform/sediment models, can be provided by the analysis of the DEM and RADARSAT images. Information on material type and drainage condition can be interpreted from the remotely sensed imagery. For example, there is a high geobotanical correlation between well-drained areas of sand and gravel and dense jack pine forest cover. Combining remotely sensed data and DEM derivatives within a GIS are a powerful method to delineate terrain units at a scale of 1:100 000. The most useful visual image sources for terrain mapping are the ETM/DEM composite and the IRS/DEM composite. Although the high resolution of the IRS does provide greater detail for terrain mapping, the ETM/DEM composite is more cost efficient and still suitable for terrain mapping at 1:100 000.

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39. Project Unit 00-32. Shale Resources of the Queenston Formation

D. K. Armstrong[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Upper Ordovician Queenston Formation is the primary source of raw material for the brick industry in Ontario. The primary area of current shale extraction and processing is in the Oakville-Hamilton-Brampton area (Figure 39.1), where the resource is located close to surface and to market. Access to the Queenston shale resource in this area is partly limited by restrictions imposed by the Niagara Escarpment Plan. In addition, increasing urbanization in adjacent municipalities is threatening access to the remaining potential resource in this area.

This study was initiated by the Ontario Geological Survey to: 1) document the properties of the Queenston Formation where it is presently quarried; and 2) evaluate potential Queenston shale resources, both in the area of current industry activity and regionally, along its entire outcrop belt. The results of this study will add to our knowledge-base of the Queenston Formation and its shale resources. This will aid in making more scientifically informed land-use planning decisions and, hopefully, help in preserving access to an important mineral resource in southern Ontario.

GEOLOGICAL OVERVIEW

The geology of the Queenston Formation was recently reviewed by Hamblin (1998, 1999). Recent studies of this formation include Brogly et al. (1998), Brogly (1984) and Donaldson (1989a, 1989b). There has been a long history of provincial government studies into the shale resources of Ontario (e.g., Rutka and Vos 1993, Guillet and Joyce 1987, Martini and Kwong 1986, Kwong et al. 1985, and Guillet 1967, 1977).

The Queenston Formation occurs in the subsurface in southwestern Ontario and outcrops – or subcrops beneath Quaternary drift cover – in a belt immediately east and north of the Niagara Escarpment from the Niagara River to Cabot Head (Figure 39.1). The formation ranges from over 300 m thick in the subsurface at Lake Erie to less than 50 m thick on the Bruce Peninsula (Hamblin 1999). The Queenston Formation also occurs in eastern Ontario. Approximately 50 m of red and green shales and siltstones assigned to the Queenston Formation are preserved there in an outlier in the Ottawa Embayment (Hamblin 1998, Williams and Telford 1986).

The Queenston Formation is the youngest Ordovician unit preserved in southern Ontario. It conformably overlies the interbedded grey-green shales and limestones of the Georgian Bay Formation and is unconformably overlain by Lower Silurian strata (Johnson et al. 1992). South of Collingwood the Queenston Formation is overlain by sandstones of the Whirlpool Formation, and northwest of Collingwood it is overlain by limestones and dolostones of the Manitoulin Formation (Johnson et al. 1992).

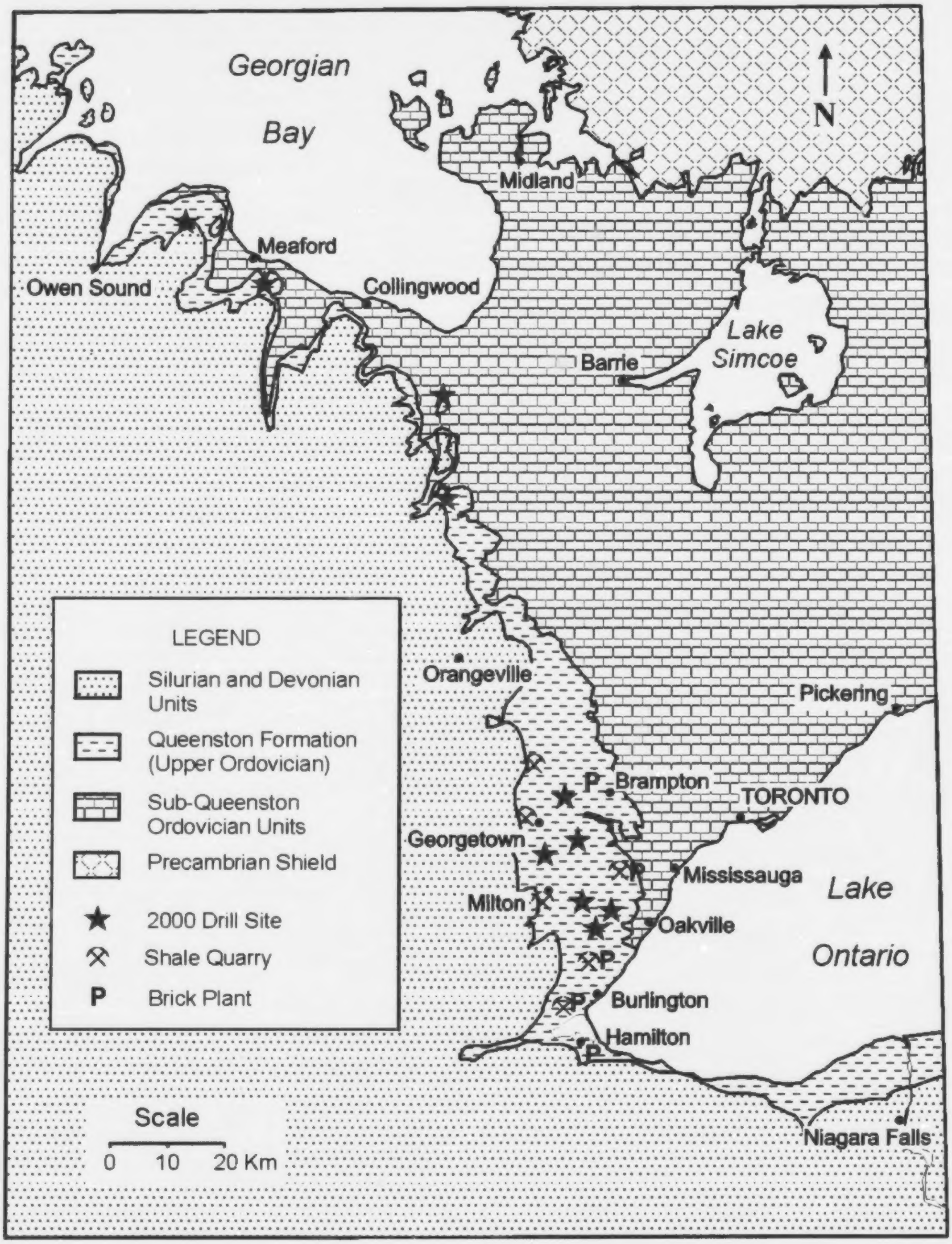

Figure 39.1. Generalized bedrock geology map of south-central Ontario, showing approximate locations of active shale quarries and brick plants, and the locations of Ontario Geological Survey 2000 drill sites (geology after Ontario Geological Survey 1991).

Commonly referred to as the Queenston "shale", this formation actually consists predominantly of silty and sandy mudstone, argillaceous siltstone, and lesser amounts of argillaceous sandstone and limestone. The formation is mainly red or red-brown to maroon in colour, with subordinate amounts of green to grey-green colour. Green colouration occurs in specific beds, as mottles, and along fractures. Much of the Queenston Formation ranges from slightly calcareous to moderately calcareous. Gypsum occurs locally as nodules and fracture fillings.

Brogly (1984) suggested an informal three-fold subdivision of the Queenston Formation in the Hamilton-Brampton area: a lower unit consisting of interbedded red mudstone and limestone; a middle unit consisting of red mudstone and abundant siltstone; and an upper unit consisting mainly of red mudstone. Donaldson (1989a) also noted a higher concentration of siltstone and calcarenite beds in the middle of the formation. In the Bruce Peninsula area, the Queenston Formation contains a distinctive middle unit, consisting of grey-green mudstones and grey bioclastic limestones (Armstrong 1993; Johnson et al. 1985). This three-fold subdivision appears to be widespread and likely represents fluctuations in relative sea level (Brogly et al. 1998).

ECONOMIC GEOLOGY

The shale extraction and brick manufacturing industry in Ontario has traditionally been concentrated in the Toronto-Hamilton-Brampton area where good quality shale resources were found close to surface and close to market. As urban areas expanded, access to shallow shales resources became more restricted. This trend of increased urbanization continues today and threatens the remaining areas of thin drift covered Queenston Formation in this area.

The locations of current brick manufacturing plants and active shale quarries are shown on the map in Figure 39.1. Three of the plants, at Streetsville, Burlington (Tansley) and Aldershot, are operated by Canada Brick. Brampton Brick operates a plant in Brampton and Century Brick operates a plant in Hamilton. Canada Brick currently extracts the Queenston shale from its quarries at Streetsville, Burlington (Tansley), Aldershot, and Milton. Brampton Brick operates the quarry at Cheltenham (north of Georgetown). Century Brick operates the A. C. Martin Quarry at Georgetown. Canada Brick also operates a quarry near Russell in eastern Ontario and owns a presently inactive quarry in the Niagara-on-the-Lake area.

The Streetsville Quarry is stratigraphically the lowest quarry; the Georgian Bay Formation strata is exposed in it's sump. The Burlington Quarry exposes the middle part of the formation. The Aldershot Quarry property likely spans the middle to upper units of the Queenston Formation. The Milton, Cheltenham and A. C. Martin quarries are all situated in the upper part of the Queenston Formation.

Although some carbonate content is acceptable in brick-making, high carbonate content and limestone are considered deleterious. Gypsum is considered an undesirable impurity in brick-making, however, its deleterious effects can be mitigated during quarrying by diluting gypsum-rich horizons with gypsum-poor strata and during processing by adding neutralizing compounds such as barium carbonate.

THIS STUDY

This study began in June 2000 with detailed examination and sampling of the presently active Queenston Formation quarries in the Hamilton-Brampton area. Sub-units were identified in each quarry and composite samples of each sub-unit were taken for geochemical analysis. Individual beds within the sub-units were also sampled for geochemical analysis. Significant outcrops and available (i.e., previously drilled) drill cores along the whole outcrop belt of the Queenston Formation were also examined and sampled in a similar fashion. Available drill cores include those drilled for other studies by the Ontario Geological Survey at Milton, Corbetton, Wiarton, and Duntroon (Johnson et al. 1983, 1985; Johnson 1983) and those drilled by the Ontario Geological Survey for a previous shale resource study (Rutka and Vos 1993). Drill core from the Niagara Falls area was also made available by Ontario Power Generation (formerly Ontario Hydro) for this study. In total, over 40 sites (quarries, outcrops, drill holes) were studied.

Potential Queenston shale resource areas were identified by reviewing available drift thickness maps (e.g., Maps 2A and 2B in, Golder Associates Ltd. and Rowell, 1996) over the Queenston Formation outcrop belt. A drift thickness cut-off of 8 m (25 feet) was used to select potential resource areas. Numerous areas of thin drift (i.e., less than 8 m) occur along the outcrop belt, except in the area between Caledon and Mansfield. Many areas of thin drift over Queenston Formation occur within the Niagara Escarpment Plan Area, in already urbanized areas (e.g., Hamilton, Burlington, Oakville and Brampton), or in areas of intense agricultural activity (e.g., Niagara Peninsula). The remaining thin drift areas are identified as potential shale resource areas.

A drilling program, designed to target potential shale resource areas (i.e., thin drift over Queenston Formation), was conducted in late summer. The objective of the drilling program was to verify drift thickness and obtain fresh samples of the Queenston shale to economically significant depths. More widely spaced northern holes were drilled to deeper depths to provide regionally significant stratigraphic information.

The drill program consisted of 10 drill holes drilled to depths ranging from 24 to 75 m. Six drill holes were sited in the Burlington-Georgetown-Brampton area, 2 in the Mansfield-Creemore area (south of Collingwood) and 2 in the Meaford-Owen Sound area (see Figure 39.1 for general locations). Specific drill hole locations, depth of overburden encountered, total depth of each drill hole and bedrock stratigraphy encountered are presented in Table 39.1.

Preliminary logs of drill cores were conducted in the field. They will now be logged in detail and sampled for geochemical analysis.

Outcrop, quarry and drill core samples were (and will be) submitted to the Ontario Geoscience Laboratories for analysis. All samples are analyzed by X-ray fluorescence for major element oxides, by IR spectroscopy for carbon and sulphur. Some samples are analyzed for chlorine and fluorine by anion analyzer.

CONTINUING WORK

Presently, drill cores are being logged and sampled. Geochemical and lithologic data from the surface (outcrops and quarries) and subsurface (new and old drill holes) will be compiled and analyzed. Results of this study will be used to generate a comprehensive characterization of the Queenston Formation shale resource in the Hamilton-Brampton area where it is presently being utilized by the brick industry. As well, the study will evaluate potential shale resource areas both within the Hamilton-Brampton area and regionally along the Queenston Formation's outcrop belt. Results of this study are expected to be released in the spring of 2001.

Table 39.1. Drill hole locations and preliminary results of Ontario Geological Survey 2000 drill program. (UTM coordinates were determined using a GPS with NAD 83 datum).

Drill Hole Number	Drill Hole Location		Overburden Thickness (m)	Total Depth Drilled (m)	Bedrock Stratigraphy (formations)
	UTM Easting (m)	UTM Northing (m)			
OGS-00-A1	597916	4811095	3.96	35.51	Queenston
OGS-00-A2	600367	4814323	3.81	34.87	Queenston
OGS-00-A4	596096	4815637	7.16	38.48	Queenston
OGS-00-A6	592246	4829873	5.79	29.49	Queenston
OGS-00-A8	587059	4826268	13.72	37.03	Queenston
OGS-00-A10	591779	4837118	13.72	24.76	Queenston
OGS-00-B1	569861	4892115	8.23	55.22	Queenston
OGS-00-B4	569122	4912183	9.14	29.26	Queenston, Georgian Bay
OGS-00-C1	532847	4932652	0.00	75.13	Manitoulin, Queenston, Georgian Bay
OGS-00-C2	520908	4944428	0.00	48.94	Queenston

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Geoscience Program Initiatives

40. Operation Treasure Hunt — Update

J.A. Fyon[1], C.L. Baker[2], G. Merlino[3], P.C. Thurston[1], R. Kelly[2], R. Dyer[2], F. Santaguida[1], R. Denomme[3], Z. Madon[3], S.W. Reford[4] and L.L. Churchill[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Sedimentary Geoscience Section, Ontario Geological Survey
[3]Data Services Section, Mines and Minerals Division
[4]Paterson, Grant & Watson Limited

WHAT IS OPERATION TREASURE HUNT?

Operation Treasure Hunt (OTH) began in April 1999 as a 2-year Government of Ontario initiative to stimulate the minerals industry. Managed and delivered by the Ontario Geological Survey, the goal of OTH is to apply state-of-the-art technology and methods to uncover exciting new mineral exploration targets that, in turn, provide investment opportunities in Ontario.

To achieve this goal, the Ontario Geological Survey (OGS) worked closely with the OGS Advisory Board (OGSAB) and Technical Committee (TC) to identify the needs and priorities of the minerals industry. The OGSAB/TC identified to the OGS geographic areas of interest.

EXTENSION TO THIRD YEAR

In July, 2000, the Honorable Tim Hudak, Minister of Northern Development and Mines announced the continuation of OTH for a third year with an additional $10 million funding. Total OTH funding over the three years will be $29 million.

OPERATION TREASURE HUNT GEOSCIENCE PROGRAM

The initial OTH geoscience program was designed to meet the needs and priorities of the minerals industry. Major program components are:

- Airborne geophysical survey program:
    - flying of new airborne geophysical surveys;
    - acquisition of existing proprietary airborne geophysical surveys;
    - preparation of an atlas and database to illustrate the location, ownership, and technical specifications of some airborne geophysical surveys over Ontario
- Purchase of lithogeochemical data sets
- Precambrian bedrock map compilation
- Compilation of platinum-palladium group element occurrences and settings
- Physical rock properties project
- Lake sediment survey program:
    - sample collection
    - PGE analysis of archived samples

- Surficial indicator mineral sampling:
    - sample collection
    - purchase of proprietary data
- Surficial geochemical methods development
- Aggregate investigations
- Industrial mineral studies
- CLAIMaps II Project
- Data management and product delivery.

The goal and status of each OTH project is described in more detail in the following section.

OTH 1999–2000 PROGRAM HIGHLIGHTS

Between April 1, 1999 and March 31, 2000, OTH program highlights include:

- flew 105 000 line kilometres of high resolution airborne magnetic and electromagnetic surveys, using the former Dighem V and High-Sense frequency-domain electromagnetic systems, former Geoterrex Geotem III time-domain electromagnetic system, and the Spectrem$_{2000}$ time-domain electromagnetic system;
- purchased about 84 190 line kilometres of existing, technically current, airborne geophysical magnetic-alone and magnetic-electromagnetic data from private sector at a discount of about 80% off current market rates to fly the same areas;
- completion of an Atlas to illustrate the location of some airborne geophysical surveys in MNDM assessment files and all OGS and Geological Survey of Canada airborne geophysical surveys;
- purchase of a lithogeochemical data base that characterizes volcanic rocks in Ontario, originally developed under the auspices of the Canadian Mining Industry Research Organization (CAMIRO);
- re-design of Precambrian bedrock compilation map product, involving client input, and public release of two 1:250 000 bedrock compilation maps covering the Quetico and Thunder Bay geographic areas (Santaguida, this volume);
- collected 8118 lake sediment samples in 3 survey areas in the northeastern and north-central portions of the province; survey areas covered 33 550 km^2 resulting in an average sample density of 1 sample per 4.1 km^2;
- geochemical method development studies over mineral deposits (gold and base metal) demonstrated that chemically reduced zones, or electrochemical cells, exist in thick glacial sediments above these features; these studies produced a number of techniques that are capable of quantitatively detecting chemically reduced zones in overburden groundwater and rock;
- CLAIMaps II – includes modification of the current CLAIMaps application to include full digital data, seamless topographic base, hot-links to mining claim data, easier navigation, and more clients products through the Internet. The application is currently being developed and is set for release in January or February of 2001; and
- Release of 84 hardcopy 1:20 000 maps and 42 CD-ROMs containing 60 gigabytes of airborne geophysical data (*see* first 2 items in this list).

PROGRAM PERFORMANCE

Positive responses from industry confirm that Government investment in geoscience contributes to mineral exploration as well as enhances the competitive advantage of Ontario to attract investment.

To address the impact of the OTH program, we monitor several indicators. Preliminary indications illustrate that OTH data has triggered staking and influenced private sector investment decisions (Churchill, Roque and Fyon, this volume). While the short-term impacts are encouraging, the true value of geoscience is realized over many years.

DATA MANAGEMENT PROJECT

The Operation Treasure Hunt (OTH) data management team are responsible for:

- ensuring that digital and analogue formats for all OTH data conform to existing Ministry standards and developing new standards where lacking;
- developing and monitoring quality assurance (QA) and quality control (QC) procedures for data capture and submissions to the Ministry by vendors;
- ensuring that metadata conforming to the Ontario government standards are completed for all digital data releases;
- ensuring that all data products are properly archived;
- establishing a timely and efficient delivery of all data products to clients.

Beginning in March 2000, the Ontario Geological Survey (OGS) released the first of the OTH data products. Over the course of this initiative, the surveys and data products listed in Table 40.1 have or will be released.

2000–2001 OTH PROGRAM PLANS

Geological surveys planned for the 2000–2001 year include:

- an airborne geophysical survey of the Dryden – Ignace – Stormy Lake area;
- a compilation of platinum-palladium mineralization and related intrusions;
- determination of physical rock properties in the Matheson and Kirkland Lake airborne geophysical survey areas;
- continuation of the 1:250 000 scale, bedrock compilation maps;
- indicator mineral sampling along the Kapuskasing Structural Zone;
- lake sediment sampling in the Sioux Lookout – Ignace and Fort Hope areas;
- industrial mineral inventories in the Grenville Province and along the north shore of Lake Superior.

Planning for the third year of OTH is in progress, in consultation with the OGS Advisory Board and its Technical Committee, in preparation for April 1, 2001.

Table 40.1. Summary of products produced for Operation Treasure Hunt.

Survey	Data Products (all figures approximate)	
	Maps/Reports	**Digital Data**
New airborne geophysical surveys • 8 surveys, totalling 137 000 line km o Cochrane o Matheson o Kirkland Lake o Temagami o Schreiber o Garden–Obonga o Vickers o Stormy Lake • Reid–Mahaffy test site survey comparing the 5 EM systems used.	103 maps at 1:20 000 87 maps at 1:50 000	55 CDs containing approximately 80 gigabytes of data in both ASCII and Geosoft® binary format, including: o profiles o grids o vector data o EM anomalies o Keating coefficient anomalies o GeoTIFF images o survey reports 16 DVDs with 60 gigabytes of half-wave data in ASCII or binary format
Procurement of existing geophysical data 11 proprietary airborne geophysical surveys purchased by the OGS, totalling 85 000 line km • Gitchie • Docker • Kakagi • Hemlo • Geco – Manitouwadge • James Bay • Dondonald – Gowan – Evelyn • Annet – Tindal • Temiskaming • Cobalt • Temagami South		Over 8 gigabytes of data on CD in both ASCII and Geosoft® binary format
Geophysical Atlas of Ontario Outline and description of all known airborne geophysical surveys flown in Ontario	2 maps at 1:1 000 000	1 Arcview GIS data set on diskette or CD
Lake sediment sampling 5 new lake geochemical surveys, totalling 21 450 samples • Armstrong – Lake Nipigon • Nakina • Foleyet – Missinaibi • Sioux Lookout – Ignace • Fort Hope	5 Open File Reports (OFR)	5 Miscellaneous Releases – Data (MRD) on diskette
Indicator mineral sampling 2000 stream sediment samples across the Kapuskasing Structural Zone for diamond-bearing kimberlite indicator minerals as well as precious metal and base metal indicator grains	2 OFRs	2 MRDs on diskette

Table 40.1. Continued.

Survey	Data Products (all figures approximate)	
	Maps/Reports	**Digital Data**
Analysis of archived geochemical samples Analysis of over 8000 archived geochemical samples (primarily for PGE and other pathfinder elements) • Garden–Obonga • Atikokan • Schreiber – Terrace Bay – Hemlo • Shining Tree • Peterlong – Radisson • Montreal River • Wawang	7 OFRs (approx.)	7 MRDs on diskette
250 000 Geological compilation maps Full colour geological compilation, including an edited subset of the Mineral Deposit Inventory (MDI2) • 52B Quetico • 52A Thunder Bay • 42D Schreiber • 42C White River • 42E Long Lac • 42F Hornepayne • 41N Michipicoten • 41K Sault Ste Marie • 41J Blind River	9 NTS quadrangles	9 digital equivalents in DGN and DXF format
Miscellaneous special studies • Electrogeochemical prospecting in areas of thick glacial overburden • Industrial white mica compilation of the Grenville • Aggregate resource inventory on the Lake Superior North Shore • CAMIRO VMS lithogeochemical data set containing approximately 1300 rock samples • Physical rock property studies in the Matheson and Kirkland Lake areas • Provincial scale compilation of platinum group element mineralization	Miscellaneous OFRs	Miscellaneous MRDs on diskette or CD

41. Project Unit 99-302. Operation Treasure Hunt: Airborne Geophysical Projects

S.W. Reford[1], E. Mueller[1], Z. Madon[2] and J.A. Fyon[3]

[1]Paterson, Grant & Watson Limited
[2]Data Services Section
[3]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

Between April 1, 1999 and March 31, 2000, the Operation Treasure Hunt (OTH) airborne geophysical program consisted of three projects:

1. fly new airborne magnetic and electromagnetic surveys
2. purchase from private sector existing airborne geophysical surveys that met technical criteria and geographic priorities
3. develop an atlas to illustrate the geographic location of some legacy airborne geophysical surveys covering Ontario.

To manage these projects, the Ontario Geological Survey (OGS) retained Stephen Reford (Paterson, Grant & Watson Limited) as project manager and OTH Geophysicist.

NEW AIRBORNE GEOPHYSICAL SURVEY PROJECT

Survey Areas and Survey Selection Considerations

Approximately 105 000 line kilometres of new airborne surveys were flown over areas of high mineral potential (Figure 41-1).

Survey areas were selected by considering:

- advice from the OGS Advisory Board;
- quantity and quality of existing OGS airborne data;
- review of proprietary airborne data available from the private sector
- known or interpreted extent of geological units and mineral targets of interest.

Both frequency-domain (FDEM) and time-domain (TDEM) electromagnetic survey systems were employed (Table 41-1). Radiometric technology was not incorporated because the surveys were flown during the winter months when snow cover would limit its effectiveness.

The FDEM was selected for areas where conductive overburden was limited, and anomaly resolution was more important than depth penetration. The TDEM was selected where thick or conductive overburden cover exists. The choice of aircraft (fixed wing or helicopter) depended on the topography of each survey area and the survey method.

Table 41-1. Summary of new airborne geophysical surveys.

Survey Name	Line kilometres	EM System
Cochrane	7,082	Geotem III - a pulse-type, fixed wing TDEM system that acquires X, Y and Z-components of the secondary field (30 Hz base frequency)
Kirkland Lake	28,264	Geotem III - a pulse-type, fixed wing TDEM system that acquires X, Y and Z-components of the secondary field(30 Hz base frequency)
Matheson	10,000	Spectrem$_{2000}$ – a full duty-cycle, fixed wing TDEM system that acquires X and Z-components of the secondary field (90 Hz base frequency)
Temagami	3,620	Geotem III – a pulse-type, fixed wing TDEM system that acquires X, Y and Z-components of the secondary field (90 Hz base frequency)
Schreiber	13,600	High-Sense – a helicopter FDEM system that acquires inphase and quadrature using three coplanar coils (865, 4175 and 33000 Hz) and two coaxial coils (935 and 4600 Hz)
Vickers	4,996	Dighem V – a helicopter FDEM system that acquires inphase and quadrature using three coplanar coils (900, 7200 and 56000 Hz) and two coaxial coils (900 and 5500 Hz).
Garden-Obonga	37,706	Dighem V – a helicopter FDEM system that acquires inphase and quadrature using three coplanar coils (900, 7200 and 56000 Hz) and two coaxial coils (900 and 5500 Hz).

The Kirkland Lake, Cochrane, Temagami and Matheson blocks (Figure 41-1) are located in mature exploration areas and, in some cases, overlap with older OGS surveys. The TDEM surveys were flown over these areas because the latest generation of TDEM technology, with its increased resolution and depth penetration, provided new insight into the geology of the region. The Schreiber, Garden-Obonga and Vickers blocks (Figure 41-1) are located in less mature exploration areas, where overburden is neither thick nor conductive. In these areas, FDEM surveys were flown.

Survey Specifications

The airborne survey systems were flown under contract by Fugro Airborne Surveys and with the Spectrem$_{2000}$ provided by Spectrem Air Ltd. under a subcontract. Each airborne system acquired both the electromagnetic and magnetic data using towed birds, providing superior resolution due to their closer proximity to the ground. The surveys were flown at 200 m line spacing, with 1500 m control line spacing.

The strike of local bedrock geology determined the flight line direction. The Cochrane and Kirkland Lake survey areas were divided into sub-blocks to accommodate local changes to geological strike.

Airborne Geophysical Survey Products

Both digital and map products in publication-ready form are available for the airborne geophysical surveys. The digital products include:

- profile database of the raw, intermediate and final data channels
- archive of the "streamed" halfwave TDEM data
- grids of the total magnetic intensity, its second vertical derivative, FDEM apparent resistivity, TDEM decay constant (tau), TDEM apparent conductivity or conductance and digital elevation model
- Keating coefficient used to identify magnetic anomalies that may correspond to circular kimberlite bodies
- electromagnetic anomaly database including model parameters
- 1:20 000 and 1:50 000 scale maps of certain grid products

- GIS-ready image and vector files of the geophysical data survey reports.

The hard copy maps consist of total magnetic intensity with flight path and EM anomalies at 1:20 000 scale.

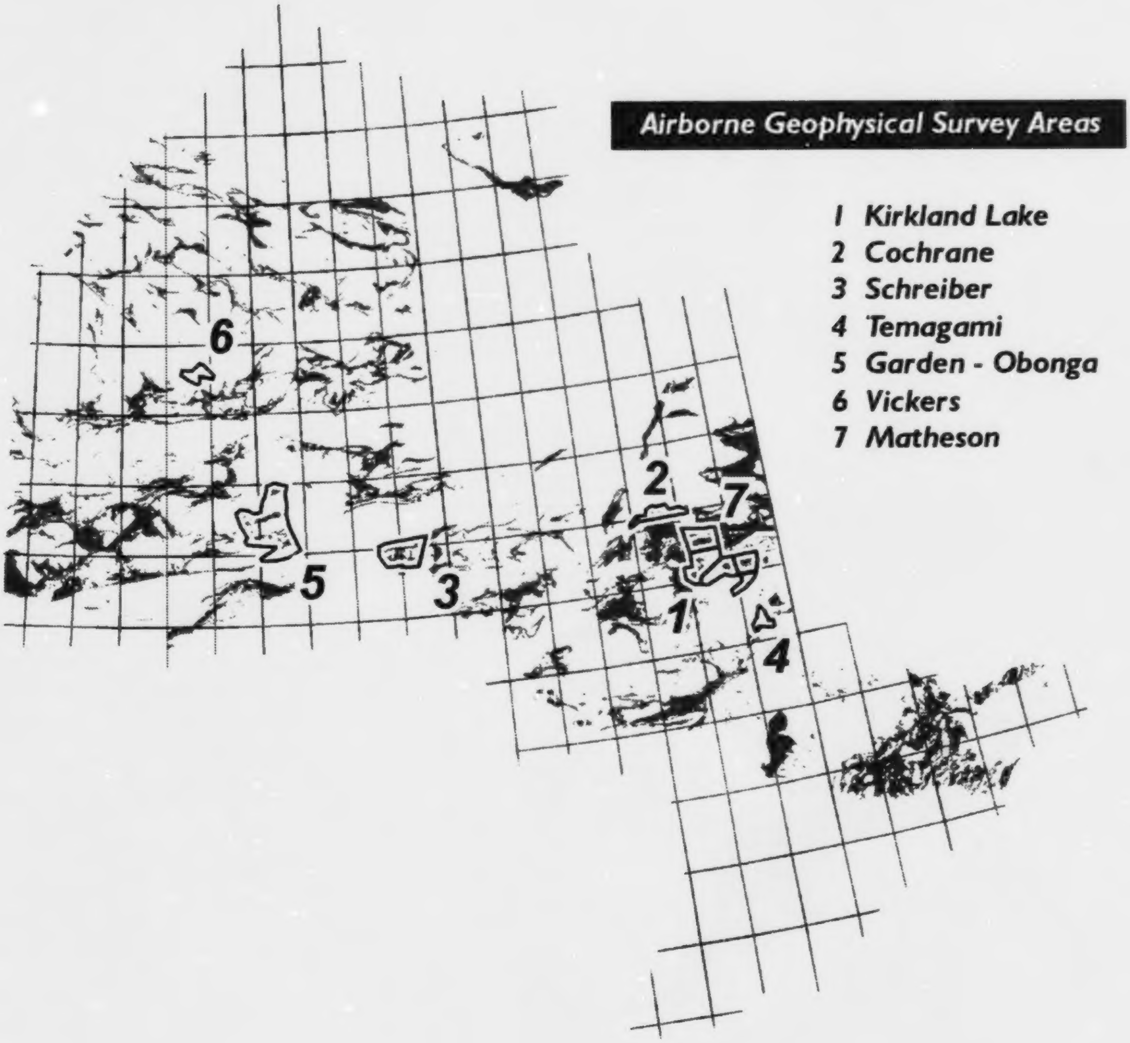

Figure 41-1. Operation Treasure Hunt Airborne Geophysical survey areas (1999-2000 fiscal year). Solid black areas represent areas of supracrustal rocks dominated by metavolcanic rocks.

OTH AIRBORNE GEOPHYSICAL TEST SITE

With the permission of Falconbridge Limited, OGS established a 5 km by 4 km test range for the OTH airborne electromagnetic systems, located in Reid and Mahaffy Townships north of Timmins. The test range contains several electromagnetic conductors that test the lateral resolution, depth penetration and overburden response of the various systems. Each airborne geophysical system flew the site along a pre-determined flight path at survey altitude. One line was flown in both directions and at a range of survey altitudes to illustrate the influence of system asymmetry and height attenuation respectively. Falconbridge Limited provided geological information, diamond drill logs, and ground geophysical data used by the OGS to provide a synthesized interpretation of the local geology to help evaluate the airborne system results.

It is planned that this site will see continued use by OGS as part of any future airborne electromagnetic survey program. The site has been flown by additional electromagnetic systems outside the auspices of OTH.

The results of the test range are aimed at the expert geophysicist. Therefore, the test range results are available only in digital format.

PURCHASE OF EXISTING PROPRIETARY AIRBORNE GEOPHYSICAL SURVEY DATA

Through an open tender process, existing proprietary airborne survey data were sought from industry to complement the existing and new government coverage. The survey data were valued using geographic, technical and quality criteria. Approximately 84,190 line kilometers of magnetic and magnetic-electromagnetic surveys were purchased (Table 41-2).

To deliver these data to clients quickly and to eliminate the need to conduct expensive and time-consuming data processing on the data, the results of these purchased, proprietary surveys will be released in digital format only.

Table 41-2. Proprietary airborne geophysical survey data purchased under Operation Treasure Hunt.

Company Name	Survey Name	Survey Type	Line Km
Barrick Gold Corporation	Gitchie	TDEM, VLF, mag	625
Noranda Inc	Docker	FDEM, VLF, mag	1,020
Noranda Inc	GECO	FDEM, VLF, mag	36,320
Spider Resources	James Bay SE	Mag	7,160
Spider Resources	Temiskaming	Mag, VLF	14,750
High-Sense Geophysics	Hemlo	FDEM, mag	15,700
Falconbridge Limited	Annett-Tindal-Browning	TDEM, mag	790
Falconbridge Limited	Gowan-Evelyn-Dundonald	FDEM, mag	1,945
Falconbridge Limited	Cobalt	TDEM, mag	450
Falconbridge Limited	Temagami	TDEM, mag	3,960
Hornby Bay Exploration	Kakagi	TDEM, mag	1,470

Explanation of abbreviations: FDEM, Frequency-domain electromagnetic survey; TDEM, Time-domain electromagnetic survey; VLF, Very low frequency electromagnetic survey; Mag, magnetic survey

AIRBORNE GEOPHYSICAL SURVEY ATLAS

An atlas of many significant airborne geophysical surveys flown over Ontario that are available in the public domain was prepared. These include:

- the historical magnetic-electromagnetic surveys flown by the OGS between 1975 and 1992
- the new OTH magnetic-electromagnetic surveys flown in 1999-2000
- the proprietary airborne surveys purchased from the private sector for OTH
- the proprietary airborne surveys submitted for evaluation but not purchased by OTH
- the historical magnetic surveys (some with radiometric and/or electromagnetic data) flown by the Geological Survey of Canada
- selected surveys documented in the MNDM assessment records.

PLANNED AIRBORNE GEOPHYSICAL SURVEY – 2000-2001

An airborne magnetic-electromagnetic survey is planned for the western Wabigoon area during October –December 2000 period, with product release scheduled for March 31, 2001.

The location of this survey and its progress is posted on the OTH web page: http://www.gov.on.ca/MNDM/MINES/oth

PLANNED AIRBORNE GEOPHYSICAL SURVEY - 2000-2001

The Fort Hope airborne geophysical survey, scheduled for acquisition during the fall 2000, was deferred to summer 2001. Planning for that survey will be completed by spring 2001.

42. Project Unit 99-316. Bedrock Map Compilation, Northwestern Ontario; Operation Treasure Hunt

F. Santaguida[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

As a part of the Operation Treasure Hunt (OTH) project initiated in April 1999, a bedrock geological compilation was undertaken for a portion of northwestern Ontario. The objective of the project is to assemble the most recent geoscience information that will generate new exploration targets.

The new maps integrate the existing 1:1 000 000 scale compilation (Ontario Geological Survey, 1991) with: 1) recent bedrock geology mapping, 2) new tectonic interpretations, 3) recent airborne geophysical surveys, and 4) the Ontario Mineral Deposit Inventory database. Publication of individual map sheets will be intermittent through to March 2001.

The project has progressed into two main stages (Figure 42.1). Initialization required the development of legends and an overall map design prior to the actual compilation. A Precambrian Geoscience Section committee defined the scope of the compilation and the various map components to be included. These components influenced map design, although the scope is governed by the project deadline.

MAP DEVELOPMENT

Definition and Design

Selection of the OTH compilation area was determined by: 1) the amount, scale and character of recent mapping, 2) the level of recent exploration activity, 3) areas of relatively high mineral potential, and 4) other active OGS compilation projects (e.g., Abitibi Subprovince Initiative, Grenville Province Initiative). The general area between Elliot Lake and Thunder Bay was chosen as the most significant region meeting the above criteria.

Following previous bedrock geological compilations that used a 1 inch to 4 mile scale (1:253 440), the new compilation maps are at 1:250 000 scale. Using this scale, map sheet boundaries are defined by the National Topographic System (NTS), so that the compilation area is divided into nine separate map sheets (Figure 42.2). The nine map sheets form three continuous map blocks reflecting geographic distribution and similarity of geologic setting. Thus, each block follows a common legend. The first two of the three map blocks to be released are shown in Figure 42.3.

Other specifications for the compilation are: projection – Universal Transverse Mercator, grid – UTM, and datum – North American Datum 27, base map – Ontario Basic Mapping (OBM), scale 1:20 000.

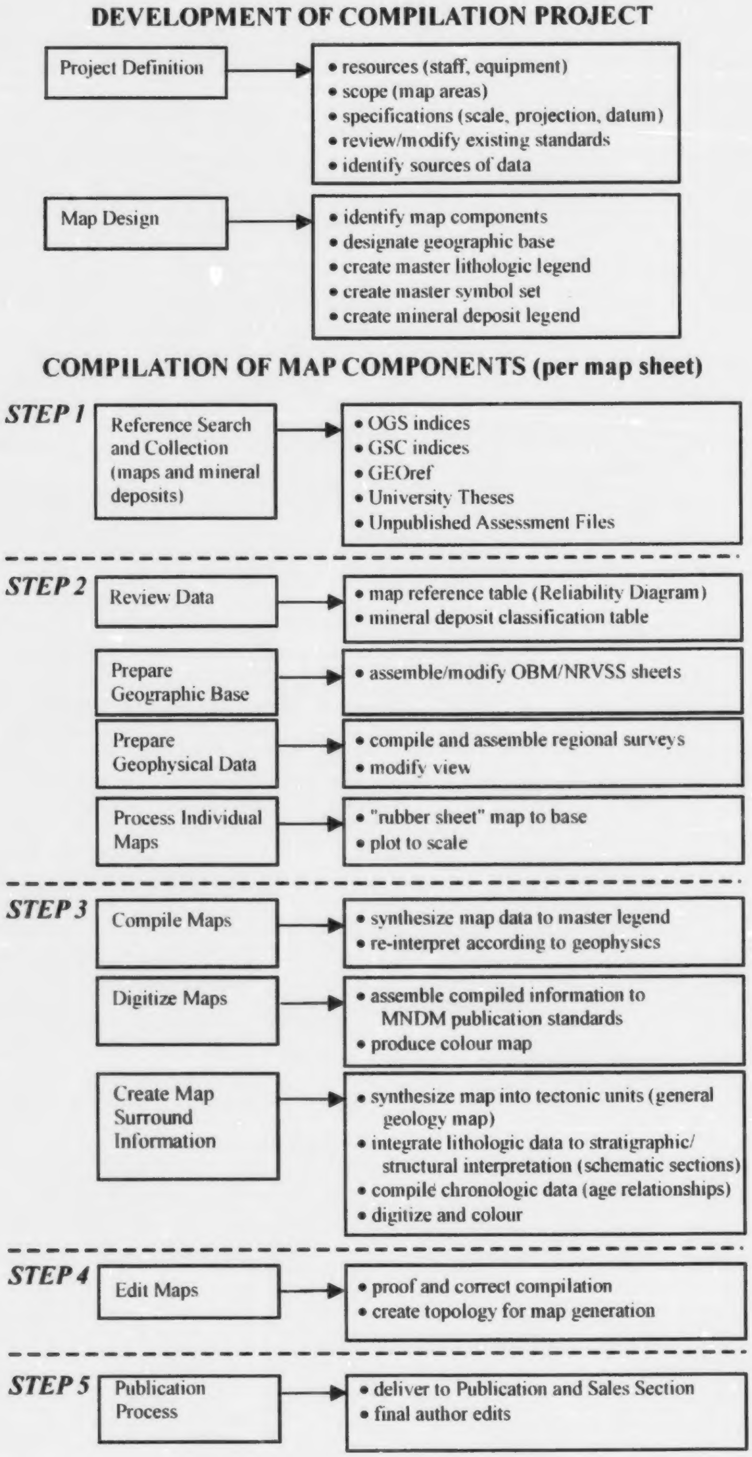
DEVELOPMENT OF COMPILATION PROJECT
Project Definition
• resources (staff, equipment)
• scope (map areas)
• specifications (scale, projection, datum)
• review/modify existing standards
• identify sources of data
Map Design
• identify map components
• designate geographic base
• create master lithologic legend
• create master symbol set
• create mineral deposit legend
COMPILATION OF MAP COMPONENTS (per map sheet)
STEP 1
Reference Search and Collection (maps and mineral deposits)
• OGS indices
• GSC indices
• GEOref
• University Theses
• Unpublished Assessment Files
STEP 2
Review Data
• map reference table (Reliability Diagram)
• mineral deposit classification table
Prepare Geographic Base
• assemble/modify OBM/NRVSS sheets
Prepare Geophysical Data
• compile and assemble regional surveys
• modify view
Process Individual Maps
• "rubber sheet" map to base
• plot to scale
STEP 3
Compile Maps
• synthesize map data to master legend
• re-interpret according to geophysics
Digitize Maps
• assemble compiled information to MNDM publication standards
• produce colour map
Create Map Surround Information
• synthesize map into tectonic units (general geology map)
• integrate lithologic data to stratigraphic/structural interpretation (schematic sections)
• compile chronologic data (age relationships)
• digitize and colour
STEP 4
Edit Maps
• proof and correct compilation
• create topology for map generation
STEP 5
Publication Process
• deliver to Publication and Sales Section
• final author edits

Figure 42.1. Bedrock map compilation project development and implementation process.

Sources of Information

The majority of geologic mapping that can be utilized at this scale is derived from OGS bedrock mapping. Geological Survey of Canada and university thesis maps are included where scale is appropriate. Assessment file maps are also used for some mining and exploration areas. Journal publications and fieldtrip guidebooks also provide essential information and interpretation to develop schematic stratigraphic sections and relative age relationships. The Ontario Mineral Deposit Inventory database (MDI2) is used for mine, quarry, prospect and occurrence information. Additional mineral deposit descriptions from OGS reports, journal publications, and fieldtrip guidebooks are also used for further interpretation.

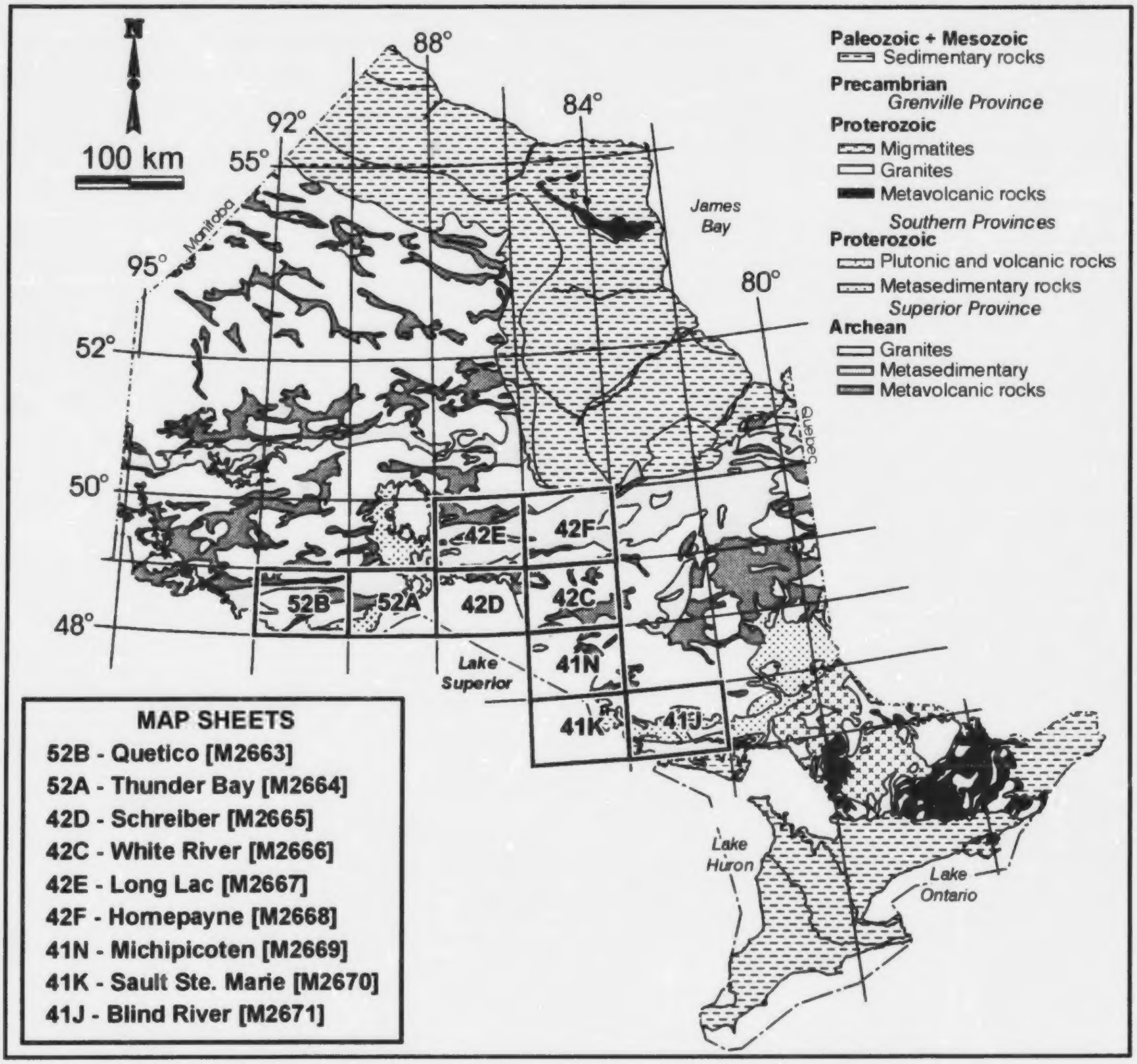

Figure 42.2. Bedrock geology map compilation areas (Operation Treasure Hunt project). The nine individual map sheets are grouped into three blocks to be published intermittently.

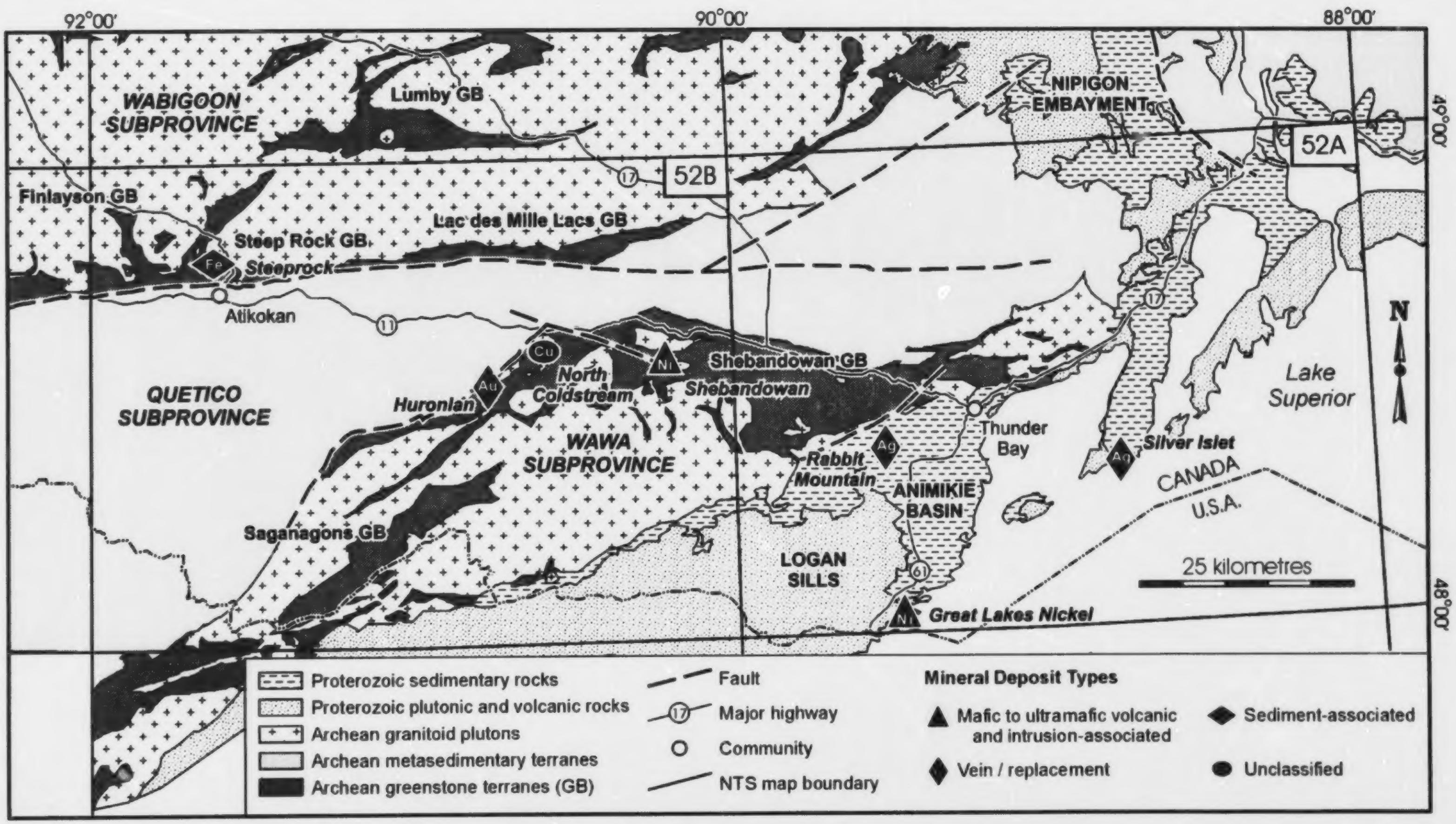

Figure 42.3a. General geology of the Atikokan–Thunder Bay area showing the two OTH compilation map sheets (Quetico – 52B and Thunder Bay – 52A). Examples of mineral deposit types for mines, prospects and districts are discussed in the text.

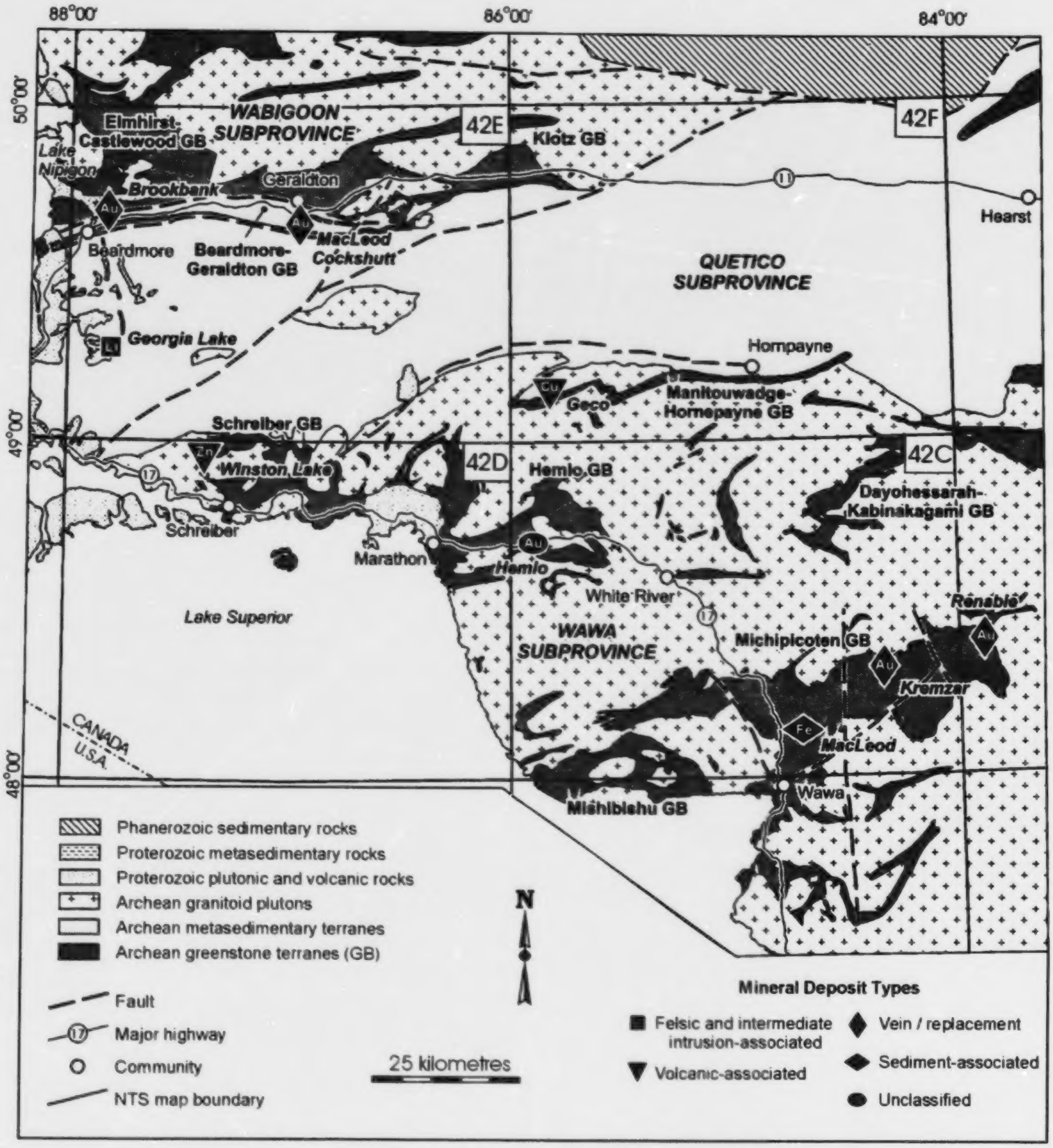

Figure 42.3b. General geology of the Beardmore–Wawa area showing the four OTH compilation map sheets (Schriber – 42D, White River – 42C, Long Lac – 42E, and Hornepayne – 42F). Examples of mineral deposits types for mines, prospects and districts are discussed in the text.

Map Compilation Methods

Digital methods are being used for the compilation to incorporate areas that have been extensively mapped and to integrate the various types of data. Digitization of all OGS Geoscience Maps as part of the ERLIS database completed in 1996 (Hum 1996) has greatly facilitated using these methods. Maps not in a digital format were digitized directly. Software utilized in the digital compilation are AutoCAD Map 2000 and ArcView 3.2. In order to digitally integrate all of the maps, each map raster image is fitted to the OBM base through a process of "rubber sheeting". Distinct geographic points (e.g., lake/river intersections, small islands, peninsulas) on the geologic map are matched with the corresponding point on the base. As a result, the map is stretched to the proper geographic dimensions. The example in Figure 42.4 illustrates the degree of distortion of an original map through rubber sheeting. The 17 points used in the example demonstrate that each point displays variable displacement depending upon its location on the map sheet. These variations reflect errors in the geographic base of the original mapping, most likely from airphoto distortion. Most displacements are greater than 1 km and are considered significant at the scale of this compilation. Due to the extent of displacement on some maps, point-source data such as mineral deposit locations and structural measurements are verified during compilation.

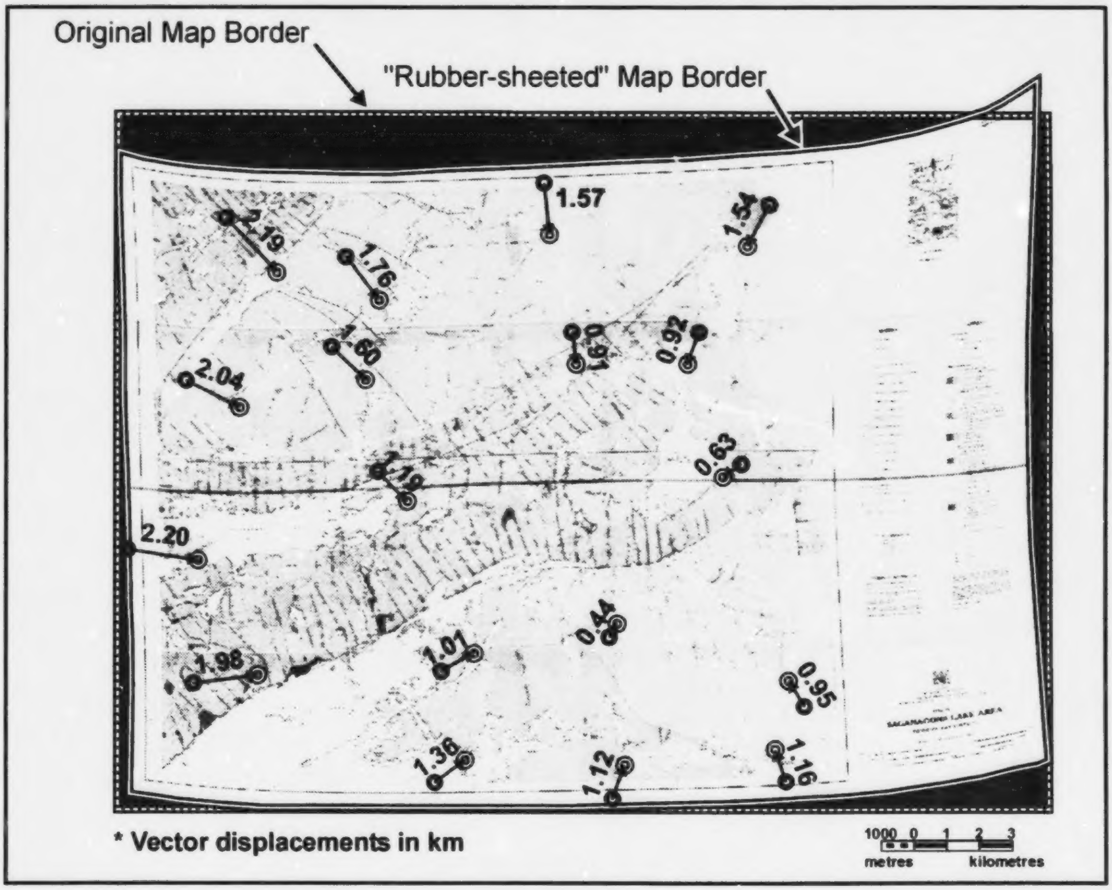

Figure 42.4. Digital map compilation by "rubber sheeting". The map is OGS Map 2149 (Harris 1968). Displacement vectors illustrate the "before/after" result of the process of fitting the map to a precise geographic base. The variable displacement reflects differential accuracy of the original map.

MAP COMPILATION

Map Components

Each compilation map is broken down into the following components: 1) a map face, 2) legend and symbols, 3) mineral deposits, 4) reliability diagram and map references, 5) aeromagnetic image, 6) sketch portraying how the sheet relates to regional geology, 7) stratigraphy, and 8) age relationships. All OGS maps contain components 1 and 2; the remaining are considered here as "map surround" of which most have appeared on previous OGS compilation maps.

MAP FACE

The map face portrays lithology, regional structures, stratigraphic interpretation (younging direction), and the distribution of mineral deposits. The map face also portrays selected geographic information such as roads, waterways, townships, park boundaries and Indian reserves. Although each map sheet is published individually, all nine sheets are continuous without overlap of information.

LEGEND AND SYMBOLS

The legend structure follows the standard OGS format with lithological units represented as numbers. The numbering system basically correlates to the known age of the units, but for most Archean rock subdivisions, increasing numbers correspond to a general age-based progression from volcanic and sedimentary to plutonic rocks. Where possible, age ranges for a particular rock unit are given in the legend. Symbols for geologic boundaries, structure and stratigraphy follow the established OGS standards (Jackson et al. 1995; Muir, Watkins and Berdusco 2000).

MINERAL DEPOSITS

Mineral deposit information is derived from the Ontario Mineral Deposit Inventory database (MDI2 –July 2000 Release). The status of each mineral deposit recorded in MDI2 is designated as: "producing mine", "past-producing mine with reserves", "past-producing mine without reserves", "developed prospect with reserves", "prospect without reserves", "occurrence", and "discretionary occurrence". Status is determined by the size and grade of the deposit that reflects a cutoff for each commodity recognized by the database. The cutoff values for each commodity are fully described in MDI2. All deposits have been included on each map sheet except "discretionary occurrence". Information for discretionary occurrences is incomplete in the MDI2 database and inclusion of these deposits within MDI2 is considered a subjective decision by an MNDM geologist. Specifically, the exact location and metal concentration for discretionary occurrences have not been verified and thus are not included in this compilation. The net effect of including only the above classes of deposits represents a small increase in the number of occurrences per map sheet. It also has the effect of presenting better data on the occurrences shown.

All mines and prospects are represented on the new maps following a metallogenic classification scheme that has been successfully used in other recent OGS bedrock compilations (Ayer, Berger and Trowell 1999; Ayer and Trowell 1998). The classification scheme is relatively simple and easily accommodates most deposits. Each mine and prospect is characterized by a symbol that depicts its type based on either host rock association or the dominant style of mineralization. The symbol is coloured based on the deposits' principal commodity. Using this system of symbols allows identification of metallogenic features such as an association of lode gold deposits with shear zones. It also serves to clearly highlight the mines and prospects on the bedrock geology maps. Examples of the various types of deposits are shown in Figure 42.3.

Most deposits are classified by the host rock association. Large iron deposits such as those in the Steep Rock area and those near the MacLeod Mine are hosted by carbonaceous iron formation and hence, considered as "sediment-associated". Massive sulphide deposits containing Ni-Cu-PGE mineralization, such as the Shebandowan Mine, are contained within anorthositic gabbro and correspond to the "mafic to ultramafic volcanic and intrusion-associated" type. This type is also used to represent disseminated sulphide Ni-Cu-PGE deposits in gabbroic rocks, such as the Great Lakes Nickel prospect, despite the contrasting geologic setting of these two individual deposits. The volcanic-associated type is characterized by Cu-Zn-Au-Ag massive sulphide mineralization in lava flows and pyroclastic rocks, as illustrated by the Winston Lake deposit (Severin, Balint and Sim 1990) and Geco deposits (Friesen, Pierce and Weeks 1982). These two deposits also exemplify the distinction between type and principal commodity. Both are hosted by felsic volcanic rocks, but at Geco, both Cu and Zn are enriched in contrast to the zinc-rich massive sulphides at Winston Lake. Felsic and intermediate intrusion-associated deposits contain a wide range of metallic commodities with diverse mineralogical relationships. The lithium-bearing pegmatites in the Georgia Lake area are examples of this deposit type.

Several other mineral deposit types are structurally controlled and do not demonstrate a direct association with their host rocks and are considered as vein/replacement type. A wide range of commodities prevail as this deposit type. Some of the most notable are the lode gold, quartz-carbonate vein deposits prominent throughout the Archean terranes within the compilation area, such as the Huronian, Brookbank, MacLeod-Cockshutt, Kremzar and the Renabie mines. Veins hosting Ag-Co-Ni-As-Bi mineralization are also included in this deposit type, which occur at Silver Islet and Rabbit Mountain.

Some deposits are not easily classified by any scheme, usually due to unique depositional settings, poorly understood mineralogical associations, or complex geological relationships in high-grade metamorphosed terranes. Rather than "pigeon-hole" these deposits into an inappropriate type, these are considered "unclassified" for this compilation. The Hemlo Au deposit is a good example of this situation. A wide range of genetic models have been ascribed to Hemlo: 1) a Mo-Au porphyry system (Kuhns, Sawkins and Ito 1994) which would be considered as a felsic to intermediate intrusion-associated type deposit, compared to 2) a shear zone-hosted system dominated by replacement-style Au mineralization (Poulsen 1996; Muir 1997) which corresponds to the vein/replacement type deposit. The Hemlo deposit is clearly distinct (e.g., size, mineralizing textures, metallic mineral associations) from the other gold deposits listed in the vein/replacement type (examples listed above); thus, to avoid confusion, the unclassified designation is used. Similarly, the origin of Cu-Au mineralization at the North Coldstream deposit is contentious due to its high degree of deformation (Osmani 1993), so it is also considered unclassified in this compilation.

The classification scheme used for this compilation is not applicable to non-metalliferous deposits such as industrial materials (talc, asbestos, garnet) and building stone (granite, syenite). Therefore, these deposits are simply symbolized as unclassified.

Distinction between producing and past-producing mines *versus* prospects is made by the size of the symbol, the smaller symbol corresponding to a prospect.

Occurrences are denoted by an "X" and its corresponding commodity is also shown next to the symbol. The occurrences are not classified by metallogenic type since most lack documentation of the geologic setting or the extent of mineralization. The MDI2 database provides an extensive list of mineral occurrences comparable in number to that shown on the previous 1 inch to 4 mile compilation maps (Table 42.1). The new maps display a slightly increased number of deposits relative to the previous series, which reflects discovery of new occurrences since the last compilation and improved database recording methods. A large increase in number is demonstrated on the 42D (Schreiber) map sheet mainly due to aggressive gold and base metal exploration in the area following the discovery of the Winston Lake area Zn-Cu-Au-Ag deposits throughout the 1980s.

GEOPHYSICS

The new compilation maps display an aeromagnetic map to further highlight regional geologic features and to illustrate the continuity of some of these features through areas of known thick overburden cover. The geophysical maps are derived from regional and detailed OGS–GSC airborne surveys. New airborne geophysical surveys are also part of the Operation Treasure Hunt project and are described by Fyon (this volume) and Reford (this volume).

Table 42.1. Numbers of mines, prospects, quarries, and occurrences in previous map compilation series *versus* the new compilation series.

PRINCIPAL COMMODITY	52A[1]	52B[2]	42D[3]	OTH52A	OTH52B	OTH42D
Au	11	32	11	13	53	48
Ag	31	3	2	38	5	11
Cu	27	30	17	15	32	37
Fe	12	18		11	25	3
Zn			6	1		18
Ni	1	10	2	1	4	7
Pb	15	1		16		4
Mo	4	4	2	3	3	6
U	1			1		2
Th						1
Nb						3
Li		3			1	
Be		2			1	
amethyst/gem	4			14		2
industrial minerals	23	11	10	4	0	2
building stone	4		1	9		10
TOTAL	**133**	**114**	**51**	**126**	**124**	**154**

[1] Data from Pye and Fenwick, 1964 (M2065); Carter, McIlwaine and Wiseby 1972 (M2232)
[2] Data from Pye and Fenwick, 1964 (M2065)
[3] Data from Carter, McIlwaine and Wiseby 1972 (M2232); Milne et al., 1971 (M2220)

REGIONAL GEOLOGICAL INSET MAP

An inset map displaying the regional geology of the map block is shown on each of the corresponding map sheets to provide an overview of the main elements for each area. These inset maps are derived from the Geology of Ontario maps and also display the major tectonic subdivisions of each area.

STRATIGRAPHIC INTERPRETATIONS

Following the format of the previous compilation series, idealized stratigraphic successions are illustrated on schematic sections for representative areas on each map. These sections are derived from detailed and regional studies using published and unpublished references. Regional faults and folds shown on the sections correspond to those highlighted on the map face. Examples of mineral deposits are also illustrated on the sections to provide an interpretation of known mineralization and to guide new exploration. At a larger scale, age relationships between greenstone belts are also shown where geochronological data are available. Section lines for each schematic are shown on the general geology inset map.

PRELIMINARY MAP REVIEW

A preliminary version of the new compilation map sheet "Quetico" (52B) was made available for comment and review prior to submission for publication. The sample map was on display in all of the Resident Geologist Offices for two weeks in June. The map was also sent to the Regional Prospector's Associations for overall comment and review. The map contained most of the proposed map components, but only displayed minimal geographic information and lacked the OGS cartographic standards (e.g., colour contrast, line weight, symbol size) that are adapted by the Publication Services Section. A questionnaire accompanying the map was devised to prompt specific comments on individual map components such as the legend structure, the mineral deposit classification system, and the overall map design. The questionnaire also aimed to identify the particular map components geologists and prospectors look for on these maps and whether these components were present on the sample map.

A summary of the review is given in Table 42.2. Eight separate pieces of map information were commented on by those who completed the questionnaire. All items commented upon by clients were considered present on the sample map, except for an identified desire for information on current exploration activity. Providing this type of information would be difficult unless the compilation map series were revised far more frequently than is now the case. Also, individual mining and exploration properties are typically too small to depict at the 1:250 000 scale.

From the comments and suggestions, several improvements to the map content and design have been made. Specific attention to increasing the amount of geographic information such as lake names and towns without impeding the presentation of geologic data has occurred. Geographic data have been added to the reliability diagram to more clearly identify the maps used in the compilation. Clarification of the mineral deposit classification scheme has been made by including an example of each element (i.e., commodity colour, symbol, symbol size). Concerns about the number of mineral deposits presented on the new maps has been addressed here by direct comparison of the previous compilation series maps and the MDI2 database (Table 42.1). Distinction between major highways and few secondary roads will be featured on the map, although road coverage beyond these is individually dependent on the amount of geological information for the area. Other comments which related to cartographic presentation (e.g., lithologic indicator numbers not legible in darkly coloured rock units) will be addressed in cartographic production.

ANTICIPATED IMPACT

The new compilation maps will directly influence mineral exploration by amalgamating the most recently developed changes in our understanding of regional geology with the accurate mineral deposit database. The new design and content of these maps link regional geology with more detailed studies and interpretations that direct the reader to more information to ultimately predict the full mineral potential of any given area.

In some cases, the new maps supersede out-of-print OGS compilation series maps (e.g., M2065; Pye and Fenwick 1964), thus a demand previously existed. Elsewhere, the new compilation maps coincide with OTH airborne geophysical surveys (Schreiber area) to present a more comprehensive geologic base for new geophysical interpretation.

Table 42.2. Summary of OTH Bedrock Compilation Map Review.

Questionnaires		
Number of questionnaire responses		16 (4 government; 12 industry)
General Comment[1]		7 positive, 8 none; 1 indefinite
Map Information[2]	1) Lithology/Structure/Legend	16
	2) Deposits	11
	3) Location/Scale	8
	4) Geography	6
	5) References	3
	6) Interpretation (stratigraphy)	2
	7) Exploration Activity	1
	8) Map Type	1
Overall Map Review/Edits		
Response by Prospector's Association	3	
Response by Resident Geologists	4	

Notes:

[1] Response to "This space is provided for other comments and suggestions not covered by the questionnaire".

[2] Response to "What three key pieces of information do you look for immediately when using a compilation map?"

ACKNOWLEDGMENTS

This project has received the ongoing advice and direction from several OGS geoscientists whose input increasingly adds to the quality of these maps and all are thanked for their contributions. In particular, Brian Berdusco has provided expert technical supervision of all of the digital compilation methods and has generated all of the geophysical maps used. His involvement in the project has been and

continues to be instrumental. The cartographic skills of Laura Hubbard, Sara-Jane McIlraith and Elizabeth Amyotte have generated top-quality products to ensure the best-possible maps. Steve Josey re-drafted some of the figures and has in turn improved the delivery of this report.

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43. Project Unit 00-303. Physical Rock Properties Study in the Matheson and Kirkland Lake Areas

S. Deschamps[1]

[1]McMaster University, Hamilton Ontario

INTRODUCTION

The goal of this project is to develop a physical rock properties database to aid in the interpretation of geophysical data used in the search for ore deposits. While geophysical data provide knowledge of regional patterns of physical property variations, the conversion of the data to images and their relationship to lithological variation cannot be achieved unless one has more knowledge on the actual physical properties of rocks.

Physical properties of concern in this study are magnetic and electromagnetic, seismic, gravity and gamma ray responses. Modern data on physical property variation in metamorphosed units of Archean greenstone belts is very scarce. Data were collected on magnetic susceptibility in an OGS project but never published. Data on density of greenstone belt rock types appear in some papers on gravity modelling of greenstone belts (Gupta et al 1982). There is also a limited data set on physical properties of mid-crustal units (Mareschal et al 1994; Salisbury and Fountain 1994).

For this project, samples were collected from two areas in which airborne magnetic and electromagnetic surveys were flown in 1999–2000 as a part of the Operation Treasure Hunt program of airborne geophysical surveys. The physical rock properties will be determined by lab work and compared to data obtained in the airborne surveys.

The field work for this project consisted of obtaining oriented samples of the major rock types in the two areas. Field sampling was divided into two areas, one in the Matheson to Nighthawk Lake region ("northern section") and the other in the Kirkland Lake to Matachewan region ("southern section"). The northern section and parts of the southern section are covered by glacial overburden that obscured much of the area making sample collection difficult. In these areas, the surface samples were supplemented with numerous diamond drill core samples obtained from the Regional Geologist's core library and from mining companies. For areas in which outcrop was plentiful, samples were taken at regular intervals of two to three kilometres, unless the rock units were of particular interest (e.g., the banded iron formation at the Adams Mine).

Two sets of samples were taken at each location, one set for the physical rock properties study to be carried out at McMaster University as a Bachelor's thesis project and another set to be used for possible thin section and lithogeochemical analysis by the OGS. Each sample taken for the physical properties study was marked in situ with an arrow indicating north and a horizontal (level) line so that it could be re-oriented in the original position in the lab. At each location, the UTM coordinates and a brief lithological description were also noted. Digital photos were taken at sample sites where tectonic and/or depositional structures were observed. In the Matheson survey, area the total number of samples taken for the rock properties study was 240 (of which 141 are diamond drill core) and, for the lithogeochemical analysis, 99 samples were taken. For the Kirkland Lake area, 232 rock property samples were taken (of which 8 are diamond drill core) and 224 samples were taken for lithogeochemistry.

The measurements that will be done on the samples include those of magnetic remanance and susceptibility, electromagnetic conductivity/resistivity, gamma ray, gravity and seismic surveys. Combinations of these measurements will help to typify mineral deposits by the nature of their physical rock property characteristics, for example:

1. Magnetic susceptibility of greenstone belt rock types will constrain magnetic models.
2. Gamma ray spectrometry defines lithologies on the basis of potassium, uranium and thorium. Changes associated with potassic alteration should then be apparent.
3. The viability of seismic methods can be established prior to a field survey by defining impedance contrast.
4. Conductivity measurements will allow determination of the spectral signature of electromagnetic conductors.
5. Knowledge of the geophysical signature of existing mineralization will permit increased efficiency of evaluation of airborne geophysical survey data.

Field work was accomplished through funding from the OGS program Operation Treasure Hunt.

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44. Project Unit 99-315. OTH Lake Sediment Geochemistry

R.Dyer

Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The Operation Treasure Hunt (OTH) lake sediment geochemistry program consists of: 1) lake sediment sampling (including lake water limnological testing); and 2) PGE analysis of archived lake sediment samples. Figure 44.1 shows the location of the project areas. These surveys cover areas of high mineral potential as well as areas traditionally considered to have unknown mineral potential. With the exception of the PGE analysis of archived samples, the survey areas were chosen based on recommendations from the technical sub-committee of the Ontario Geological Survey Advisory Board. These areas have not previously been sampled by the Ontario Geological Survey (OGS) or during the National Geochemical Reconnaissance (NGR) lake sediment program carried out jointly by the Geological Survey of Canada and the OGS during the late 1970s and early 1980s.

The fieldwork for these lake sediment surveys was carried out by private contractors under contract to the OGS. Standard OGS sampling methodologies were utilized (see OGS 2000a and 2000b) and adherence to these OGS protocols was monitored by OGS staff as detailed in the quality control section below. Samples collected during the 1999 field season were prepared and analyzed by a private lab under contract to the OGS. Samples collected during the 2000 field season are being analyzed by the Geoscience Laboratory in Sudbury.

LAKE SEDIMENT SURVEYS

Fieldwork for project areas A (Foleyet), B (Nakina) and C (Armstrong) was completed in 1999. Open File Reports (OFRs) for lake sediment project areas A and C were released in April and September, 2000 respectively (OGS 2000a and 2000b). The OFR for Area B will be released in December 2000 (OGS, in press). Fieldwork for project areas D and Fort Hope was completed during the period June to September 2000. Samples from these areas are currently being analysed. A combined total of over 21,000 lake sediment samples have been collected and submitted under the auspices of OTH.

PGE ANALYSIS OF ARCHIVED SAMPLES

PGE analysis of archived lake sediment samples was completed during the spring/early summer of 2000. This involved archived samples from 8 project areas as follows:

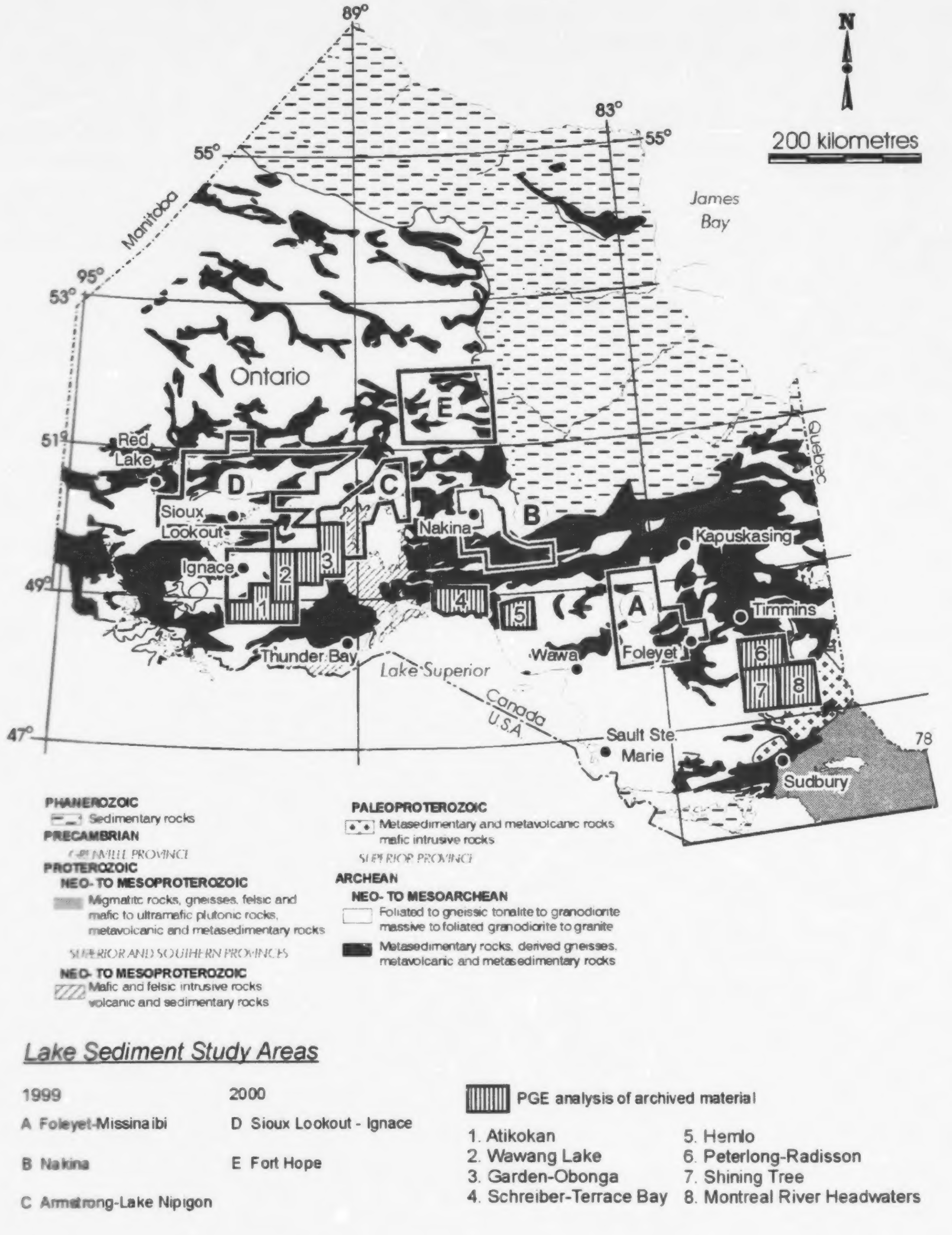

Figure 44.1. Location of Operation Treasure Hunt Lake Sediment Surveys.

1. Garden-Obonga
2. Wawang Lake
3. Atikokan
4. Schreiber-Terrace Bay
5. Hemlo
6. Shining Tree
7. Peterlong-Radisson
8. Montreal River headwaters

The data for the Garden-Obonga area was released in July 2000 (OGS 2000d). The Schreiber-Terrace Bay, Hemlo and Atikokan datasets are scheduled for release in December 2000. It is anticipated that the remaining PGE datasets will be released in early 2001.

ANALYTICAL METHODS

Laboratory analysis consisted of nitric-aqua regia digestion of 0.5 gm of sample pulp followed by inductively coupled plasma-mass spectrometry (ICP-MS) and inductively coupled plasma-optical emission spectroscopy (ICP-OES) to determine approximately 50 trace elements. Nitric acid-aqua regia digestion attacks all sample matrix constituents, except for silicate minerals, and therefore is considered a nonselective, relatively strong partial extractant. Approximately 10 gm of sample pulp was pressed into briquettes prior to analysis by instrumental neutron activation analysis (INAA) for Au, As and a suite of 25 other elements. If sufficient sample pulp was available, 15 grams of material was analyzed by fire assay with ICP-MS finish to determine Au, Pt and Pd. Loss-on-ignition (LOI) was determined at 500°C, using a standard furnace-gravimetric technique.

QUALITY CONTROL/QUALITY ASSURANCE PROCEDURES

Quality control/quality assurance (QC/QA) in the field is crucial to a successful geochemical sampling program. Quality control involves: (1) proactive measures at the time of sample collection; and (2) quality assurance procedures at all stages of the sample collection/handling/analysis process. To ensure that OGS protocols were adhered to, a rigid quality assurance program was instituted to ensure the integrity of samples collected and data acquired. The program involves 4 components:

1. A mandatory information and training session for the contractor prior to the commencement of field work. Follow-up information sessions and/or field visits by the OGS staff were done to ensure all aspects of sample protocols and requirements were understood and were implemented by the contractor.
2. The collection of method (field) duplicates by OGS staff at approximately 2% of lakes sampled. This procedure is intended to provide a fair determination of the contractor's performance with respect to sample collection and handling techniques, maintenance of water quality measuring equipment and recording of sample site locations. Field duplicates were sequenced-in with the Quality Control samples following fieldwork. After accounting for losses in precision due to analytical limitations, a level of precision of the field duplicate pairs is required to meet specifications outlined by the OGS. The analytical precision is determined from Thompson-Howarth plots (Thompson and Howarth 1978)

using analytical data from sample pulp duplicates inserted into the sample batch(s) by the OGS. The field duplicate precision (also using Thompson-Howarth plots) is determined for all elements but a group of 5 indicator elements and LOI are used to rank the reproducibility of duplicates. Failure to meet the specifications outlined by the OGS resulted in monetary penalties;

3. The insertion of Quality Control samples by the OGS, including method (field) duplicates, homogenized sample duplicates and certified reference standards (to determine laboratory accuracy) into the sample sequence between sample preparation and laboratory analysis. Every 10th sediment sample submitted was a quality control (QC) sample. The QC sediment samples consisted of field duplicates, analytical (pulp) duplicates, certified reference standards (CRS) and an internal (OGS collected) bulk standard. Field (method) duplicates were inserted with a frequency of 1 in 40. Analytical pulp duplicates were prepared by halving 1 in 40 of the dried sample pulps and inserting them into the sample sequence. CANMET certified reference standards (LKSD 1 to 4, Lynch 1990) and an OGS internal standard were also inserted as dried pulps between the sample preparation and analysis stages. Every 20th sample was either a CRS or an OGS internal standard. These 3 standards were inserted alternately so that each was repeated every 60th sample;
4. Monetary penalties for the collection/submission of inorganic samples and inadequate sample size.

RESULTS AND SUCCESS TRACKING

To date, over 100 significant discrete multi-site and/or multi-element anomalous areas have been delineated by the OTH lake sediment program. In excess of 2000 claim units have been staked as a direct result of the published datasets. The OGS is also aware of several property transactions that have occurred as a direct result of these surveys and will continue to follow and track such success stories. The publication of the Area B (Nakina) dataset and the PGE analysis datasets over the course of the winter will certainly further increase the number of significant anomalies and result in further exploration activity.

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45. Project Unit 00-305. OTH Indicator Mineral Surveys

R.Dyer

Sedimentary Geoscience Section, Ontario Geological Survey

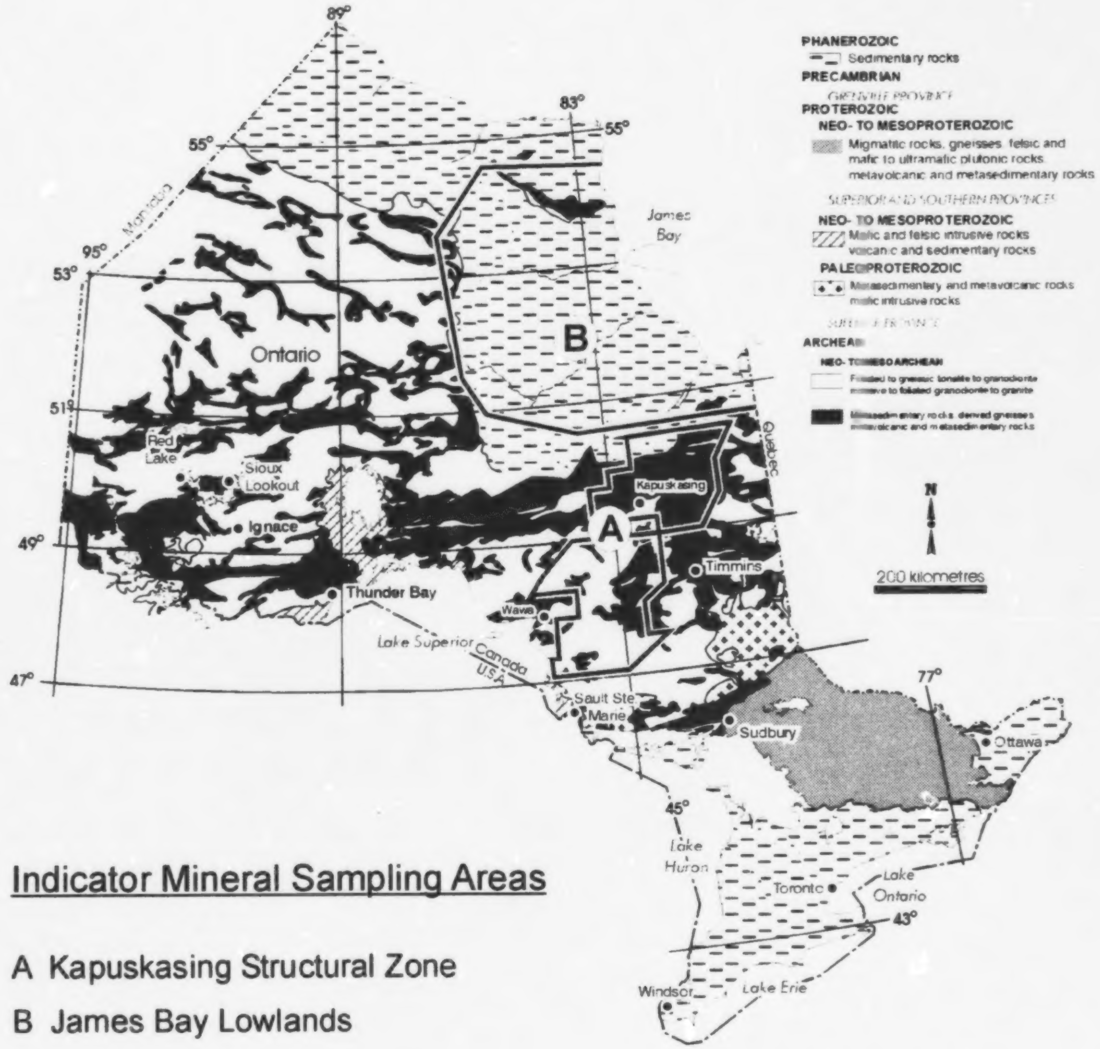
INTRODUCTION

Modern alluvium sampling for indicator minerals was carried out over the Kapuskasing structural zone (KAPZ) during the summer of 2000 (Figure 45.1). This project is one of 2 indicator mineral projects planned under Operation Treasure Hunt (OTH); the other project, under consideration for 2001, will involve sampling of large rivers draining the James Bay Lowlands. Traditionally, the modern alluvium sampling program of the Ontario Geological Survey has undertaken low to medium density sampling over structurally favourable shield terrain in Ontario in conjunction with Quaternary mapping. The OTH program over the KAPZ involved medium density (approximately 1 sample per 30 km^2) sampling over an area of approximately 65 000 km^2. Approximately 2000 samples were collected and are being processed to isolate kimberlite indicator minerals, magmatic massive sulphide indicator minerals (MMSIM®) and gold grains. It is expected that the maps, reports and databases generated by this survey will help focus exploration efforts of prospectors and exploration companies.

The fieldwork for this survey was carried out by a private contractor under contract to the Ontario Geological Survey (OGS). Standard OGS sampling methodologies were utilized (see Morris and Kaszycki 1997, Morris et al. 1997, Stephenson et al. 1999) and adherence to these OGS protocols was monitored by OGS staff as detailed in the quality control section below. The samples are being processed by Overburden Drilling Management in Nepean and microprobe work is currently ongoing at the Geoscience Laboratory in Sudbury.

SAMPLE PROCESSING

At the lab, a 10 to 18 kg split is disaggregated, if needed, and sieved to remove the +10 mesh (+2 mm) size fraction. The entire –10 mesh size fraction is passed across a shaker table twice to produce a rough heavy mineral concentrate. Samples, in which a pre-determined number of gold grains are seen during shaker table processing, have the heavy mineral (table) concentrate refined by hand or mechanical panning to concentrate all contained gold grains and associated pathfinder minerals. Following the panning (if required), the tabled heavy mineral separates undergo a heavy liquid separation. The specific gravity of the heavy liquid used during this procedure is 3.2. Following heavy liquid separation the magnetic minerals are separated using an automagnet. The paramagnetic fractions (weakly, moderately, strongly and nonparamagmetic fractions) are isolated using appropriate methodology. This final heavy mineral concentrate (HMC) is seived to obtain 4 size fractions (<0.25 mm, 0.25-0.5 mm, 0.5-1.0 mm, 1.0-2.0 mm), each of which is weighed and placed in vials. Indicator mineral picking is then performed on the 0.25-0.5 mm, 0.5-1.0 mm and 1.0-2.0 mm size fractions. A scanning electron microscope is used to confirm/check any questionable picked grains. The indicator minerals are then submitted to the Geoscience Laboratories for microprobe analysis. This determines the chemical composition of the grains and whether their source was from a kimberlite.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55°
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49°
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45°
43°
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Manitoba
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Red Lake
Sioux Lookout
Ignace
Thunder Bay
Kapuskasing
Timmins
Wawa
Lake Superior
Canada
USA
Sault Ste Marie
Sudbury
Ottawa
Lake Huron
Toronto
Lake Ontario
Windsor
Lake Erie
PHANEROZOIC
Sedimentary rocks
PRECAMBRIAN
GRENVILLE PROVINCE
PROTEROZOIC
NEO- TO MESOPROTEROZOIC
Migmatitic rocks, gneisses, felsic and mafic to ultramafic plutonic rocks, metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
NEO- TO MESOPROTEROZOIC
Mafic and felsic intrusive rocks, volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary and metavolcanic rocks, mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite, massive to foliated granodiorite to granite
Metasedimentary rocks, derived gneisses, metavolcanic and metasedimentary rocks
N
200 kilometres
Indicator Mineral Sampling Areas
A Kapuskasing Structural Zone
B James Bay Lowlands

Figure 45.1. Location of Operation Treasure Hunt indicator minerals projects

QUALITY CONTROL/QUALITY ASSURANCE PROCEDURES

Quality control/quality assurance (QC/QA) in the field is crucial to a successful indicator mineral sampling program. Quality control involves: (1) proactive measures at the time of sample collection; and (2) quality assurance procedures at all stages of the sample collection/handling/analysis process. To ensure that OGS protocols were adhered to, a rigid quality assurance program was instituted to ensure the integrity of samples collected and data acquired. The program involves 4 components:

1. A mandatory information and training session for the contractor prior to the commencement of field work. Follow-up information sessions and/or field visits by OGS staff were done to ensure all aspects of sample protocols and requirements were understood;
2. The collection of method (field) duplicates by the OGS. This procedure is intended to provide a fair determination of the contractor's performance with respect to sample collection and handling techniques and recording of sample site locations. Field duplicates were sequenced-in with the Quality Control samples following fieldwork;
3. The use of bulk sample weight and table feed weight criteria to ensure performance requirements have been met by the sample collection Contractor;
4. The application of penalties proportional to the degree of non-performance of OGS protocols and procedures.

PROJECT STATUS

A total of 1910 samples were collected and submitted to Overburden Drilling Management for processing. At the time of this writing, approximately half of this total had been processed and the picked grains submitted to the Geoscience Laboratory for microprobe work. It is anticipated there will be a staged release of the data during 2001.

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46. Project Unit 00-306. OTH Aggregate and Industrial Mineral Surveys

R.Dyer

Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

The OTH program includes both a bedrock aggregate resource evaluation and an industrial mineral project. The aggregate project is focused on evaluation of high-quality bedrock aggregate sources along the north shore of Lake Superior, while the industrial mineral project is focused on white mica potential in southeastern and central Ontario (see Figures 46.1 and 46.2). These projects were awarded to private contractors following the evaluation of competitive bids to request for proposals. Fieldwork for these projects commenced in August 2000. It is expected that final maps and reports will be published in 2001.

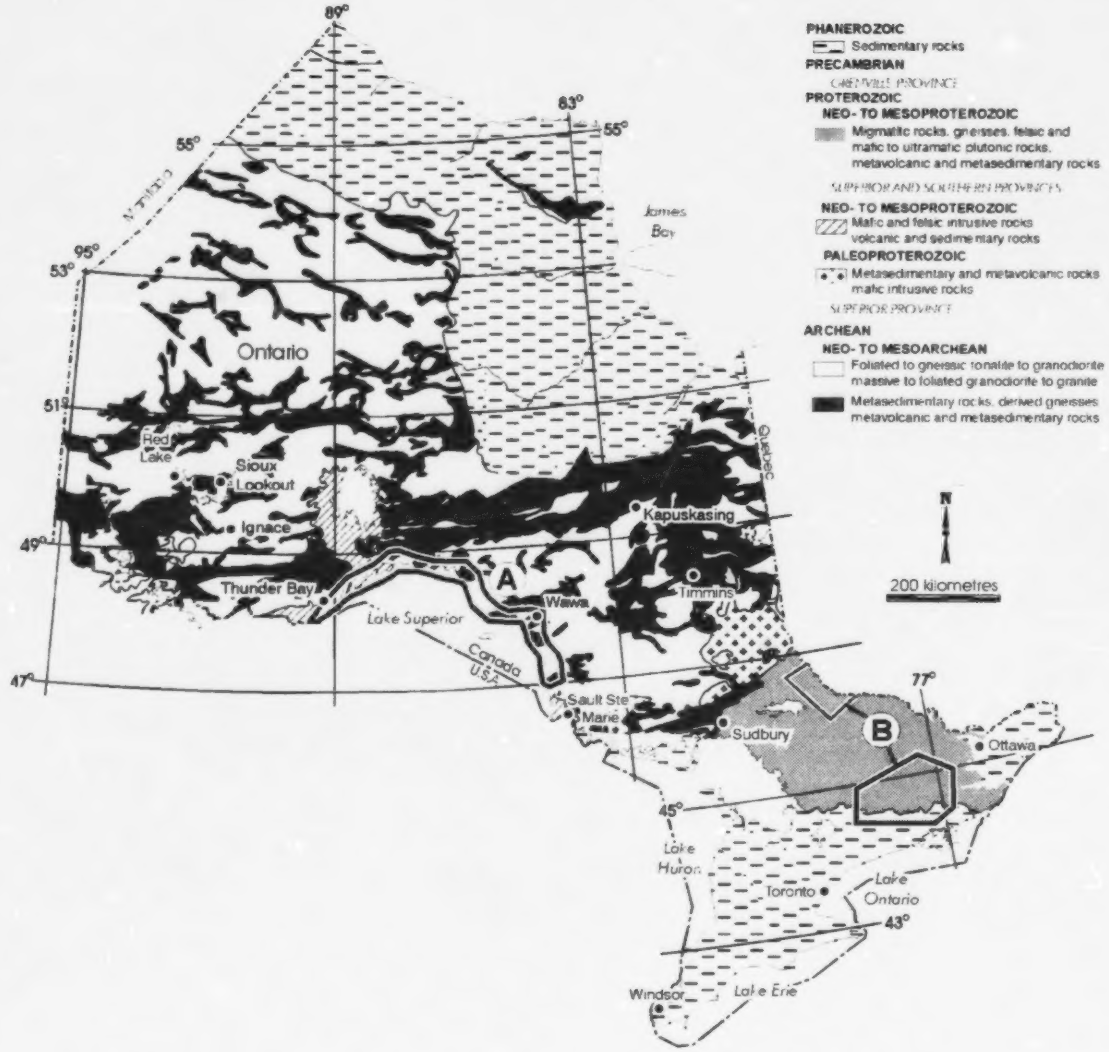
BEDROCK AGGREGATE RESOURCE POTENTIAL ALONG THE NORTH SHORE OF LAKE SUPERIOR

As aggregate resources in Ontario, particularly southern Ontario, are depleted and/or sterilized, other areas of the Province must be explored and evaluated for their aggregate potential. The bedrock units along the north shore of Lake Superior represent one such potential resource area. Similar investigations have been undertaken along the north shore of Lake Huron between Bruce Mines and Massey (Ontario Geological Survey and Dames & Moore, Canada 1995; Ontario Geological Survey and Golder Associates Ltd. 1996).

Of particular interest to these studies are "high end/value" bedrock aggregate resources, such as trap rock (diabase), suitable for asphalt applications in 400 series highways. Once potential bedrock aggregate locations have been identified, an evaluation of the macro economic factors in developing the resource will be undertaken. This might include such factors as: 1) existing and future markets; 2) current and projected demand for the aggregate; 3) transportation costs to markets; 4) methods of transportation; 5) development of water transportation facilities (e.g. depth of water, type of vessels, etc.); and 6) overall feasibility of developing the resource area. The results of this work will be an Open File Report and a series of Bedrock Resource Maps indicating the potential aggregate resource areas.

WHITE MICA POTENTIAL, SOUTHEASTERN ONTARIO

The mica assessment and sampling program is designed to undertake an investigation and sampling of mica-rich bodies to identify deposits that may provide suitable sources of, specifically, flake "white mica". White mica has various applications and end-uses, such as in paints, rubber and as filler in body panels of automobiles. The project also requires testing of samples from prospective sites to determine


PHANEROZOIC
Sedimentary rocks
PRECAMBRIAN
GRENVILLE PROVINCE
PROTEROZOIC
NEO- TO MESOPROTEROZOIC
Migmatitic rocks, gneisses, felsic and mafic to ultramafic plutonic rocks, metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
NEO- TO MESOPROTEROZOIC
Mafic and felsic intrusive rocks volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary and metavolcanic rocks mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite massive to foliated granodiorite to granite
Metasedimentary rocks, derived gneisses metavolcanic and metasedimentary rocks
N
200 kilometres
89°
83°
55°
55°
95°
53°
51°
49°
47°
45°
43°
77°
Manitoba
James Bay
Ontario
Quebec
Red Lake
Sioux Lookout
Ignace
Kapuskasing
Thunder Bay
A
Wawa
Timmins
Lake Superior
Canada
U.S.A.
Sault Ste Marie
Sudbury
B
Ottawa
Lake Huron
Toronto
Lake Ontario
Windsor
Lake Erie

Aggregate and Industrial Minerals Project Areas

A Aggregate Study Area, north shore Lake Superior

B Industrial Minerals (White Mica) Study Area

Figure 46.1. Operation treasure Hunt Aggregate and Industrial Minerals Projects

chemical and physical properties. As well, the project requires an assessment of current markets, uses and future trends for white mica use.

Work completed by the Ontario Geological Survey in southeastern Ontario has identified a number of mica bodies that may have potential to host economic deposits of white mica (e.g., Hewitt 1968, Kingston et al. 1985). In addition, the Ontario Mineral Deposits Inventory (MDI) database contains over 200 mica occurrences in southeastern Ontario.

The current project is being conducted to increase our knowledge of mica bodies that may host potentially valuable deposits, undertake testing and analytical work required to assess physical and chemical properties, and finally assess markets and trends for use. The maps, reports and databases generated by this program are designed to help focus exploration efforts of prospectors and exploration companies interested in white mica in all parts of Ontario.

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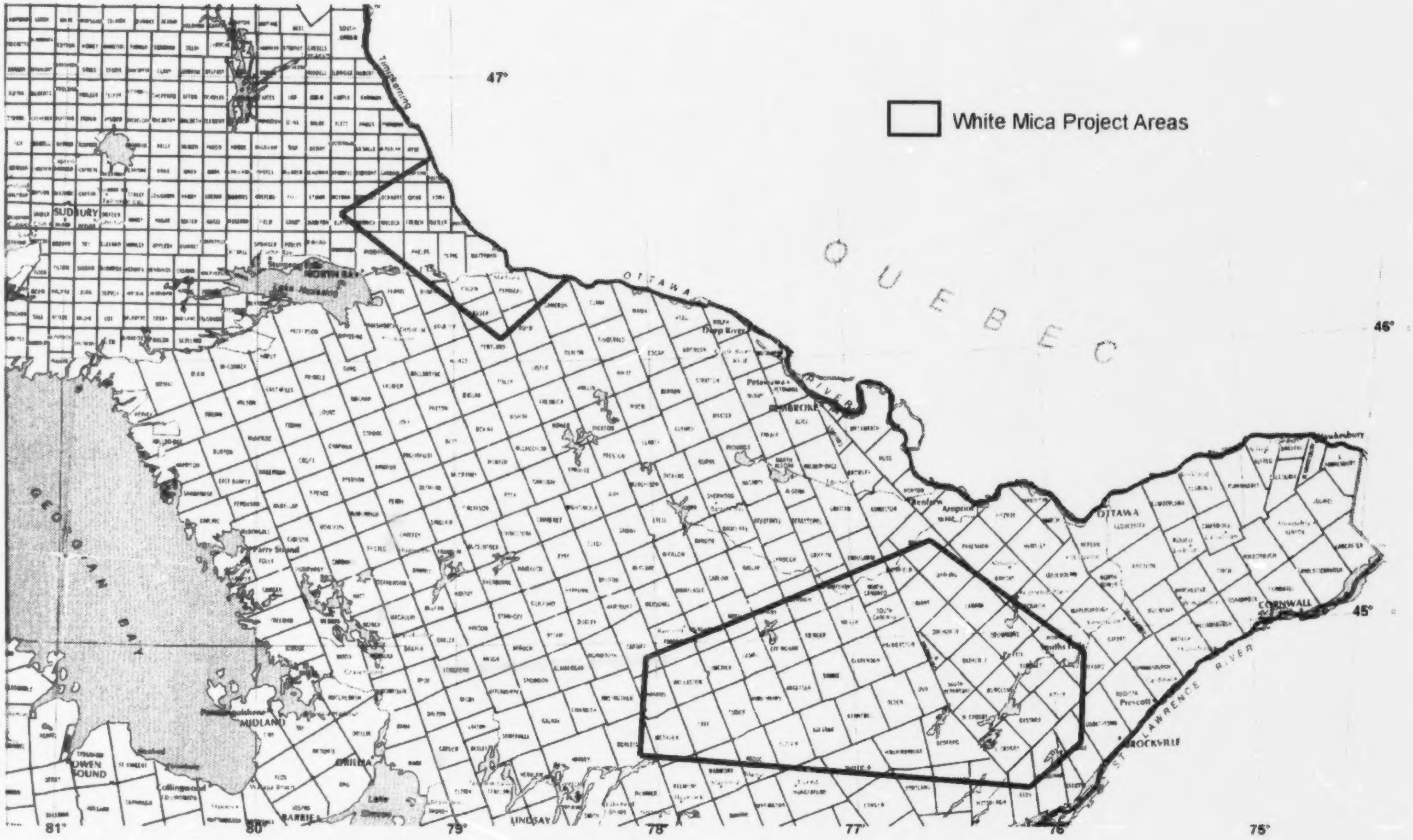


Figure 46.2. White mica project areas

47. Project Unit 99-318. Thick Overburden Geochemistry – Methods and Case Studies

S.M. Hamilton[1], D.R. Cranston[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

This phase of the Ontario Geological Survey (OGS) Thick Overburden Geochemistry project (TOG) forms part of the Operation Treasure Hunt (OTH) methods development initiative. Hamilton (1999) provided an overview of the objectives of the TOG and results obtained up until that time. As it currently stands, the program has 3 components each with different partners. The first component is concerned with developing and refining electrochemical tools that can be used for mineral exploration in areas of thick overburden. This work is being carried out predominantly by the OGS. The second is a joint program between the OGS, the Geological Survey of Canada (GSC) and the Canadian Association of Mining Industry Research Organisations (CAMIRO) that is investigating selective leach geochemical methods in thick overburden environments at 3 known mineral occurrences. The third involves the investigation of the electrochemical and geochemical character of a number of "forest rings", which are large circular features in boreal forests that are thought to be centred on geological sources of negative charge. This latter project has been carried out in collaboration with the Diatreme Explorations Incorporated and J. Veillette of the GSC. These partnerships are expedient because the shared resources and expertise produce greater results than could be achieved by any 1 of the partners working alone. The results of all aspects of the OGS contributions to the partnerships are to be considered public domain and will be published as soon as is practical.

The methods development work is being carried out on 6 sites as described below. The study is attempting to establish methodologies for measuring the redox characteristics in earth materials, i.e., for differentiating areas that exhibit positive or negative electrical charge in overburden, groundwater or rock. In addition to testing techniques, it has the practical goal of testing the OGS theory (Hamilton 1998, 2000a) that chemically reduced (negatively charged) zones exist over mineralisation and other reduced geological features in areas of thick overburden and that these are, in turn, responsible for many of the selective leach anomalies observed in those environments. Because the methods are experimental and each is problematic under certain conditions, as many techniques as possible have been used. The results so far have been encouraging and reduced zones have been detected on 20 of the 21 lines surveyed at the 6 sites despite glacial overburden thicknesses exceeding 50 m in some cases.

In the CAMIRO-partnered investigation surface geochemical sampling was carried out on 3 mineral deposit sites: the Marsh Zone, owned by St. Andrew Goldfields Limited; Cross Lake Mineral's Sheraton township property; and the Half Moon Lake property, held by Prospector's Alliance Limited (PAL). The Marsh Zone is a syenite hosted gold deposit overlain by clay and peat and the other 2 sites are base metal properties overlain by sand/clay and clay respectively. The overburden thicknesses vary from 20 to over 50 m. The Marsh Zone and Cross Lake were selected for detailed subsurface investigations. Drilling programs were carried out on both sites this year and some of the results are presented below.

There are 3 forest-ring sites being investigated in detail; 1 north of Hearst and the other 2 north of Timmins. They were selected for their accessibility by road. At the time the investigation was initiated, the causes and processes that formed the rings were unknown. However, an initial orientation survey in the fall of 1998 provided sufficient data to support our hypothesis that the rings were centred on geological sources of negative charge. All 3 of the sites have since been drilled, with mostly shallow auger holes, but several holes were also drilled to rock. Some results are described below.

A huge amount of data has been collected and is currently being compiled for release in 2001. This summary represents an overview of the methods, data and results that will be presented in that (or those) report(s). The data are overwhelmingly supportive of the occurrence of electrochemical mass and charge transport of ions related to the presence of buried mineralisation in thick overburden environments.

METHODS DEVELOPMENT

The electrochemical and geochemical methods development program has the broad goal of developing new, and improving existing, geochemical techniques for detecting mineralisation and other bedrock features through thick glacial overburden. Previous work on this subject by the OGS (see Hamilton 1999) included soil sampling and comparison of various selective leach procedures, measurement of spontaneous potentials (SP) in association with mineral deposits and theoretical studies.

It has become apparent in the last few years that the electrochemical migration of metals along redox gradients may be responsible for many of the geochemical anomalies that have been detected in relation to buried mineralisation. Therefore, in order to understand geochemical transport mechanisms, the redox characteristics of the overburden and groundwater environments must first be quantified. Unfortunately, redox measurement is one of the most poorly developed of all analytical techniques. Consequently, the most important objective of this phase of the methods development program has been to develop protocols and methods that can measure redox and electrochemical charge in the earth more effectively. As mentioned, as many different techniques as possible were tried. Despite their experimental nature, a surprising number of these appear to have worked.

The procedures used to quantify the redox character of earth materials are briefly described below and will be described in greater detail in the final report. These procedures are important to the other 2 components of the project because they have been used to demonstrate that chemically reduced areas exist over the features being studied. Some examples of this are provided in the following 2 sections.

Surface Spontaneous Potential

Three different techniques were tested for the measurement of surface SP. The conventional technique of using 2 asbestos-bottomed, Cu-$CuSO_4$ half-cell porous pot electrodes, was used on many sites. It involved measuring the voltage difference between a stationary and a mobile electrode connected by a long reel of wire. An improvement on this technique was tested on a number of sites that involved replacing the mobile pot with a porous bottomed (lathed oak) Cu-$CuSO_4$ "lance" that could be jabbed into the peat. This allowed faster and more consistent placement of the electrode and was intended to reduce noise effects due to the very near-surface variability in moisture content of the peat. The third technique tested was to use a platinum-tipped lance instead of the mobile Cu-$CuSO_4$ electrode to penetrate the saturated peat.

Of these methods, the Cu-$CuSO_4$ lance appears to be the most effective in dry to moist areas. The initial findings indicate that the Pt-tipped lance was most effective in fully saturated peat environments, although data from only 1 site has been examined. Furthermore, the platinum lance takes at least 1 minute per reading and this might prove excessive in large surveys.

The greatest problem with surface SP occurs due to the variable moisture content of soils. At present, the technique works best in relatively dry environments. It may be possible to develop protocols for uniformly moist environments, however, these are likely to work less effectively. In thick overburden environments with highly variable moisture content, the technique is not likely to be useful because the voltages due to moisture-related noise (up to 60 mV) are typically greater than the voltages that could be expected to occur due to mineralisation.

Down-hole SP

In addition to the electrochemical noise due to moisture, profound effects due to the degree of oxidation have also been observed. The degree of oxidation is related to the water table depth, media type (e.g., clay vs. sand) and permeability. One way to get around, or rather under, these effects is to use a CME drill rig to auger shallow holes to depths beneath the zone of oxidation and beneath the water table. A number of auger-hole transects were made across features being studied at the various sites and monitoring wells were installed in each hole. Down-hole SP was measured across the feature at the successive well sites using platinum-tipped electrodes referenced against a stationary Cu-$CuSO_4$ half-cell electrode.

Two types of electrodes were used. On the 2 sites drilled in the winter of 1999, 3 platinum tipped wires were affixed at different depths to the outer part of the plastic monitoring well casings as they were being installed. The end of the wire exposed on surface provided a direct electrochemical connection to the overburden/groundwater environment outside the well at each of the 3 depths. Although some useful data came from down-hole SP measurements made by this technique, the results are somewhat erratic. Part of the reason for this is likely that the exposed wire on surface allowed current leakage between more reduced areas at depth and the oxygenated surface. This could only have happened during wet periods when the wires were moist due to rain or snow cover but may have occurred often enough to have caused oxidised deposits to accumulate on the platinum thereby affecting the voltage measurements during the SP survey.

An apparently better down-hole technique was used at the 2 initial sites and the 3 that were drilled this year. It involved successively lowering the same platinum-tipped wire down into the groundwater column in each well and taking SP readings in the well screen. Again, these measurements were referenced against a stationary Cu-$CuSO_4$ electrode on surface. A number of refinements were tried in an attempt to produce an optimum methodology. Notwithstanding a few problems with this technique, it produced good results, some of which are shown in the sections below. In short, it showed significantly more negative results in areas that are considered, by other corroborating evidence, to overly reduced geological features.

Down-Hole Redox Measurements on Split-Spoon Samples

On the 3 sites drilled this year, split spoon samples were taken at 3 or 4 depths prior to the installation of monitoring wells. The samples were predominantly clay and were mixed into a slurry using a small measured volume of distilled water within 1 hour of collection. Samples were then tested for pH and by 2 different oxidation-reduction potential (ORP) procedures. One was to use an untreated redox probe and the other was to pre-treat an identical probe with an acidic ferrous-sulphate solution. This, in theory, pre-polarised the probe and allowed a faster response time. ORP measurement is notorious for its slow equilibration with the sample and therefore, all measurements were taken at 1, 2 and 5 minute intervals from the time the probe was inserted in the sample.

This process required great uniformity in the treatment of the samples and probes because of the extreme sensitivity of ORP probes to polarisation. A detailed description of the methodology will be forthcoming in the final report. Notwithstanding the method's sensitivity, at times it produced excellent results, some of which are shown below.

Surface Redox Measurement of Soils

On most of the sites, soil samples were extracted and, within a predetermined time period, tested for pH and treated and untreated ORP. Measurements were taken according to the protocols used for the split-spoon samples. Peat was extracted from a depth of about 0.5 m below surface and was tested by simply inserting the probes, excluding air by squeezing the bag and taking the readings. Clay samples and humus samples were tested after first mixing a slurry. Results by this method were also favourable but with shallow samples, such as peat, they show only a partial expression of the redox phenomena that are occurring at depth.

Groundwater Redox Measurement

Originally, the intent of the monitoring wells had been to establish the position of the water table and to provide a rigid PVC support on which to attach the platinum tipped wires. However, when groundwater was extracted and measured using conventional ORP probes in a flow cell, the results were quite favourable. Two variations on this were tried. One that extracted standing water from inside the well screen without purging the well and a second that extracted it after pumping the well down and allowing it to recover. Because so many of the wells were finished in fine-grained materials and thereby took days to recover, the air was expelled from the purged wells with nitrogen to limit the oxidation of the water column during recovery. Both techniques appear to work well. It has not yet been determined if the extra effort to purge the wells and expel the air was worth the trouble since not all the data are currently available.

OGS-GSC-CAMIRO: MARSH ZONE AND CROSS LAKE PROJECTS

The OGS-GSC-CAMIRO study involves the study of a number of known mineral deposits that are overlain by at least 20 m of glacial overburden. From an initial list of about 80 sites and a shortlist of 15, 3 were selected for detailed surface geochemical investigation (Hamilton 1999). Of these, 2 were considered appropriate for subsurface geochemical investigations – the "Marsh Zone" and the Cross Lake site.

The investigation at these 2 sites involved 3 phases. The first, undertaken in the summer of 1999, was to characterise the surface geochemical and electrochemical signature by soil sampling and by measuring surface SP. The second was a drilling phase. The Marsh Zone could only be accessed in winter and was drilled in February 2000 whereas Cross Lake was drilled in June of 2000. During the drilling, samples were collected and field measurements for ORP and pH taken. The third phase, involving down-hole measurements and groundwater sampling could not proceed until after the wells had equilibrated. This phase is ongoing as of September 2000.

Marsh Zone

The mineralisation at the Marsh Zone contains an estimated 5 to 10% pyrite. Other sulphides have not been noted but may be present. The "syenite" zone which, compositionally, is actually an albitite (B. Berger, OGS, personal communication, 2000) is approximately 5 m thick and is vertically oriented. The deep hole drilled into rock on Line 15 at 15 m south (Figure 47.1) encountered subcropping mineralisation at a depth of 20.5 m. Diamond drill records show that mineralisation is flanked to the south by talc-chlorite schist (altered ultramafics) and to the north by talc-chlorite schist and then by mafic metavolcanic rock beginning at about 40 m north. The overburden thickness is about 10 m at 200 m south, thickening to 27 m at 60 m south and then thins steadily to 18 m at 25 north. The glacial drift is known to thin north of this but the exact thicknesses are not known. None of the 8 m deep auger holes drilled on line 15 encountered any material other than glaciolacustrine clay. It is thought that overburden thickness is no thinner than about 10 m anywhere on the line.

Some of the results from the field data collection for the summer of 1999 and the February, 2000 drill program are shown in Figure 47.1. The peat pH data (0.5 m depth) show a general increase from the centre of the line to the outer edges, perhaps due in part to decreasing peat thickness. However, it also shows some strong central trends that are not related to peat or overburden thickness. Two of the lowest pH readings occur 15 m north and 25 m south of mineralisation. The highest pH occurs approximately over the mineralisation at 10 m south (this pH value was at first discounted because it was not measured within 12 hours but it has since been corroborated by high analytical solution pHs).

Surface SP (Figure 47.1) shows very little noise and a distinctly increasing trend across the site from south to north. This trend shows a central dip over mineralisation that is more apparent as a residual of the regression line through the data. The pH trends may be due in part to peat thickness trends but since the peat has a uniform thickness of 2 m between 0 and 100 m south and since the low is clearly centred over mineralisation at 15 m south, there is a likelihood that mineralisation also plays a role.

The best field data that has so far come from the Marsh Zone is the subsurface redox data gathered by mixing and testing clay slurries during the drill program. Samples were collected by split spoon and measured within 1 hour in a heated tent. The results (Figure 47.1) show a strongly reduced column over mineralisation from the clay surface to at least 6m depth. A strong smell of H_2S was noted during subsequent groundwater sampling of the bedrock well in this central area.

Figure 47.2 shows surface geochemistry for the Marsh Zone. Superimposed on the plot for each figure is the second principal component derived from a principal components analysis of the peat geochemical data. The purpose of principal component analysis is to reduce a large number of variables in a set of data to only a few, while losing only a small amount of information. It does this by determining the co-dependency of many variables and extracting combinations of elements, or "components", in the data that contribute to the variability of the data in similar ways. In geochemical data, different components would usually result from different geochemical processes. In geochemical data sets with dozens of variables, there may be numerous components extracted but usually only a few dominate.

In the case of the peat samples for the Marsh Zone, the first principal component appears to be related to the peat thickness and degree of weathering of the underlying clay and/or humification of the peat and will not be discussed further here. The second principal component, however, appears to be related predominantly to mineralisation (Figure 47.2). The component weights for each element are shown in Table 47.1. A positive weight contributes to the positive variability of the component whereas a negative weight contributes to the negative variability. A weight close to 0 indicates little contribution of the variable to that component. The elements shown on Figure 47.1 are 4 of the strongest positive and strongest negative contributors to the variability of the second principal component.

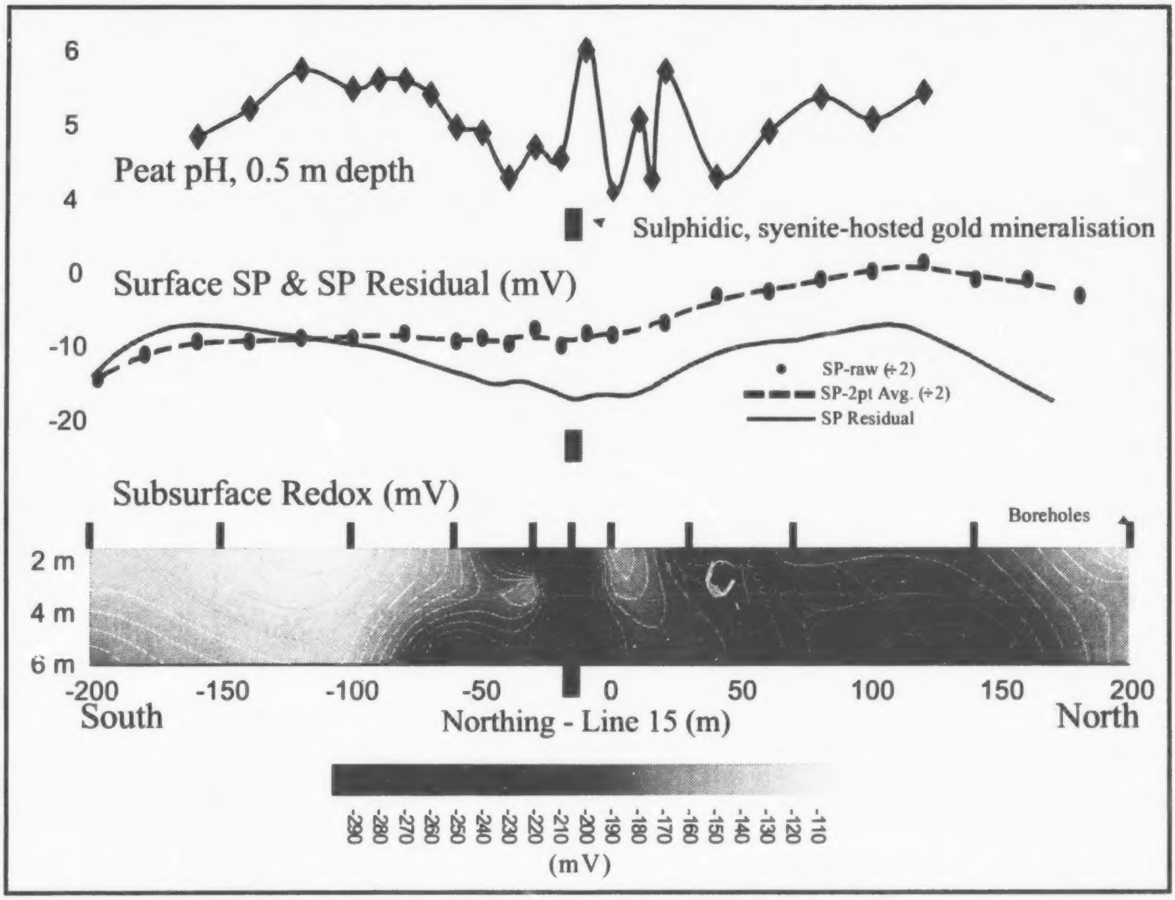


Figure 47.1. Surface pH and SP of peat and subsurface redox of clay, Line 15, Marsh Zone.

Interestingly, most of the strong contributors to the negative variability are elements from the Na-pyrophosphate dataset whereas most of the strongest contributors to the positive variability are from the aqua regia dataset. Na-pyrophosphate analysis is a selective-leach procedure designed to selectively extract metals adsorbed to organic phases (Hall et al. 1996). Aqua regia, being a strong acid, extracts most or all of the metals in a sample including metals in the mineral soil matrix, where it is present. This apparently suggests that the most mobile components of the metals are not only being accumulated in surface peat straddling mineralisation but that they are also being depleted in the area immediately over mineralisation. Electrochemical processes are the only one of various possible mobility mechanisms that can singly account for depletions over mineralisation.

Although it is not obvious from Table 47.1, organic carbon shows a very strong depletion immediately over mineralisation. As a result, the strong positive correlation in elements by aqua regia may be due to removal of organic carbon and a resulting concentration of the clastic component of the peat. Govett and Chork (1977) noted organic carbon depletions over mineralisation in thin-overburden environments and attributed these and other factors to electrochemical processes.

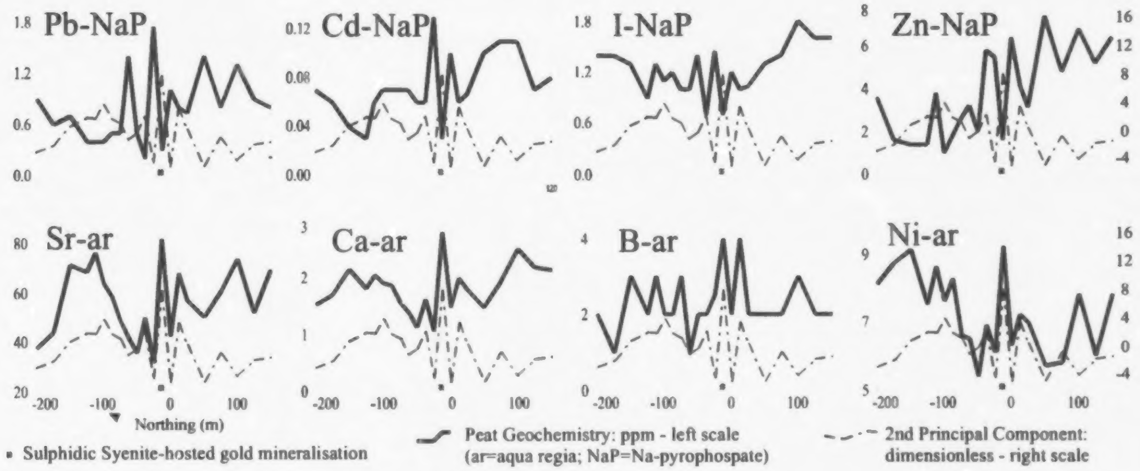


Figure 47.2. Geochemistry and second principal component, Line 15, Marsh Zone. Elements plotted on the first and second rows, respectively, contribute to the negative and positive variability of the data.

Parameter	Component Weight	Parameter	Component Weight	Parameter	Component Weight
Sr - aqua regia	0.181183	Zr - aqua regia	-0.00111415	HR - Na-Pyro	-0.123651
Sol'n pH - Na-Pyro	0.169873	Mn - Na-Pyro	-0.00194871	Bi - aqua regia	-0.137143
Ca - aqua regia	0.148948	K - aqua regia	-0.0045779	Sb - aqua regia	-0.146697
B - aqua regia	0.147658	Fe - aqua regia	-0.0266195	W - Na-Pyro	-0.158446
Ni - aqua regia	0.145439	Li - Na-Pyro	-0.0286474	Cr - Na-Pyro	-0.163252
Ag - Na-Pyro	0.142114	Cd - aqua regia	-0.0380294	Zn - aqua regia	-0.164589
Peat Thickness	0.124084	Ga - aqua regia	-0.0402088	Th - Na-Pyro	-0.167691
Na - aqua regia	0.110463	Rb - aqua regia	-0.044984	[H+] - peat	-0.17098
Mg - aqua regia	0.105889	C - Na-Pyro	-0.0557949	Co - Na-Pyro	-0.171638
Sr - Na-Pyro	0.101049	Rb - Na-Pyro	-0.0864427	Nb - aqua regia	-0.176253
Cu - aqua regia	0.0881553	Ca - Na-Pyro	-0.0883514	Au - aqua regia	-0.182494
Mo - Na-Pyro	0.0776301	P - aqua regia	-0.0911514	Ga - Na-Pyro	-0.185855
Mn - aqua regia	0.0745335	As - Na-Pyro	-0.0932345	Pb - aqua regia	-0.201471
Se - Na-Pyro	0.0608827	LREEs - Na-Pyro	-0.106447	Zn - Na-Pyro	-0.201875
Mo - aqua regia	0.0587421	Fe - Na-Pyro	-0.106839	Sn - aqua regia	-0.214479
Mg - Na-Pyro	0.0467009	K - Na-Pyro	-0.109937	I - Na-Pyro	-0.214794
Ag - aqua regia	0.025301	Eu - Na-Pyro	-0.113719	Cd - Na-Pyro	-0.231184
Y - aqua regia	0.020522	Ni - Na-Pyro	-0.113801	Hf - Na-Pyro	-0.233088
Th - aqua regia	0.00111718	Y - Na-Pyro	-0.11562	Pb - Na-Pyro	-0.237988

Table 47.1. Component weights for the second principal component. A positive weighted element contributes to the positive variability of the component whereas a negative weighted element contributes to the negative variability. A weight close to 0 indicates the element contributes little to the variability of the component. Since a limited number of variables could be used, those with no visible central trends in the data were removed prior to carrying out principal component analysis.

Cross Lake

The mineralised zone at Cross Lake contains sphalerite, chalcopyrite and pyrite. The total sulphide content is up to several 10s of percent. The zones on lines 40 and 6 (Figure 47.3) dip approximately 70° to the south. Overburden on line 40 consists of dry sand south of mineralisation and to about 50 m north. To the north, peat and muskeg overlies moist to saturated sand that is underlain by clay at depths that shallow to the north from 6 to less than 3 m. When drilled, the thickness of overburden on line 40 was 51 m, which was somewhat greater than had been anticipated. Line 6 is underlain by clay that is dry and oxidised in some places and saturated and largely unoxidised in others. Thin humus overlies the clay in dry areas whereas thin peat has accumulated in the low, moist areas. The hole drilled to bedrock at 200 south on line 6 encountered bedrock at 29 m, which was well mineralised with abundant pyrite, sphalerite and small amounts of chalcopyrite. The hole drilled to rock at 1420 south on line 40 encountered only trace amounts of sphalerite, a few percent pyrite and no chalcopyrite. Either the zone does not subcrop here or the hole intersected the footwall rocks.

Figure 47.3 shows field parameters for line 6 from the 1999 summer program and June 2000 drill program. Conventional surface SP shows a low over mineralisation and trends related to ground surface elevation and the resulting changes in soil moisture. The trends show the typical and paradoxical increase in SP in wetter areas and decrease in dryer terrain. Although the area around 200 south is dry and a low is expected here, the SP is more negative within 25 m of mineralisation than anywhere else in the northern 600 m of line 6. The likelihood that this is due to mineralisation is corroborated by the ORP data from split-spoon slurries. In the samples from 1.5 m depth, the redox potential is higher in the upland dry areas and lower in the gullies, where the high, artesian water levels limit the oxidation of the clay. Over the mineralisation a distinct low is noted that is not related to either moisture content or elevation.

This low was noted in both sets of ORP data: those for which the probe was treated for 30 seconds (as were data shown for the other 3 ORP plots on Figure 47.3); and those for which it was treated for 60 seconds in the ferrous sulphate pre-treatment solution. Both show lows within 25 m of mineralisation that are difficult to account for by other processes. However, the centre of the low is right over the mineralisation in the 60-second pre-treatment data whereas it is 25 m north of it in the 30-second data.

As a footnote on the 2 ORP datasets, each show a similar trend but the probe treated for 60 seconds has a more negative background and lows have twice the negative magnitude of those treated for 30 seconds. This appears to be due to both the idiosyncrasies of the probe (identical Orion model 13-641-1186 probes) and the different pre-treatment protocols. Without pre-treatment, the 60 second probe read close to the true value of a particular standard whereas the 30 second probe read about 100 mV higher. On the other hand, it appears that the 60 second probe was over-prepared during a series of earlier readings and was more sensitive to reduced conditions than was the 30 second probe. This appears to have been an advantage on the more oxidised 1.5 m samples, where it responded better to the subtle increases in redox negativity of the clay. However, for the deeper samples, it resulted in low positive relief in the data that may not have accurately shown the trends that exist in ORP across the site. This discrepancy, albeit minor, exemplifies some of the problems with obtaining reproducible ORP data from probe to probe, site to site and protocol to protocol.

The ORP data from the deeper split spoon samples shows even more obvious lows over mineralisation. The samples are from below the zone of oxidation and the ORP low at 200 south is sufficiently pronounced that it is difficult to account for it other than by the presence of mineralisation. The cause of the persistent ORP low at 350 south is unknown.

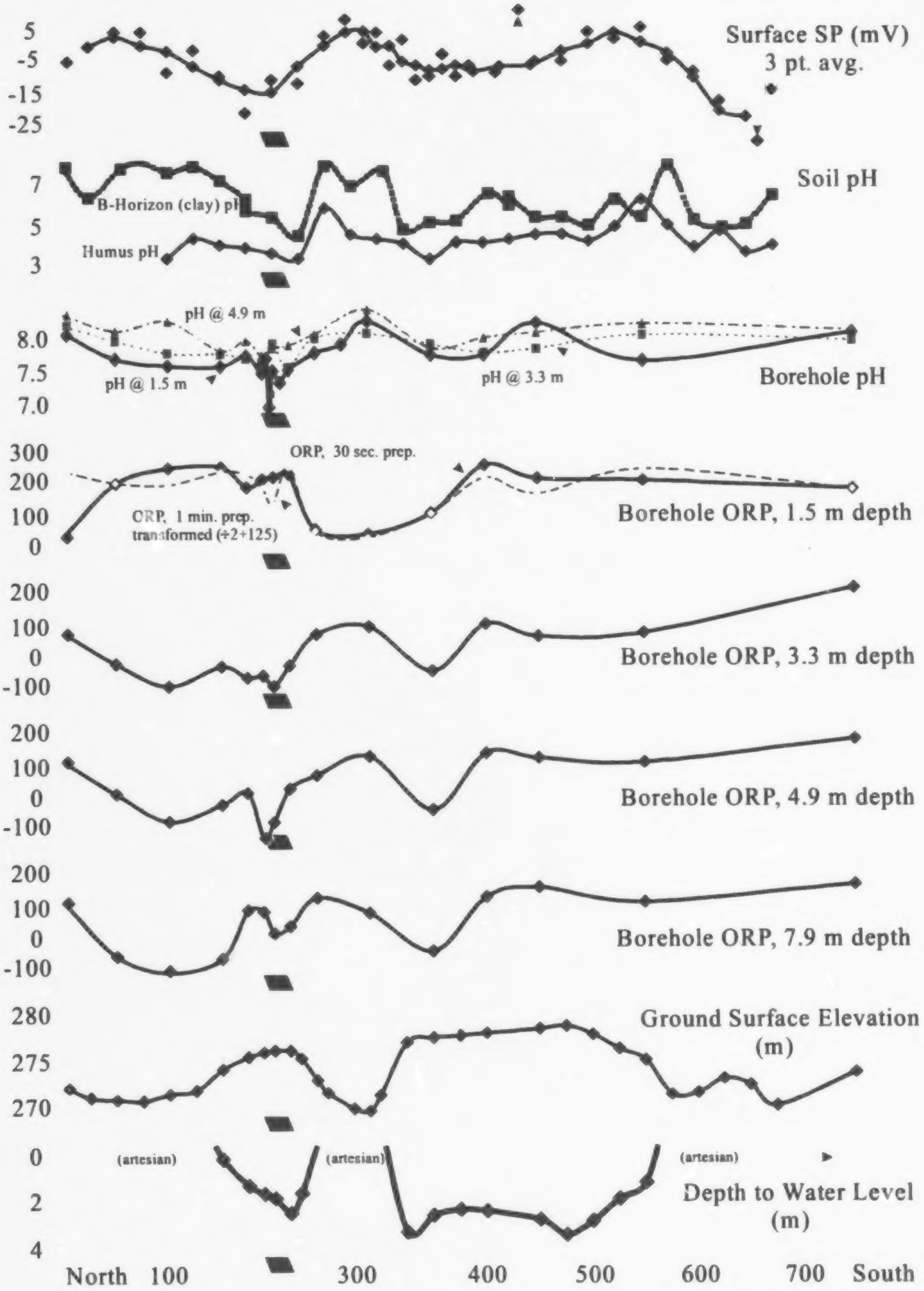


Figure 47.3. Field parameters for Cross Lake, Line 6. The south dipping mineralisation is shown at 200 m south.

Both surface and subsurface pH data show a marked low in the vicinity of mineralisation. The lowest pH values on the entire line for each of the of the 4 clay data sets shown are within 25 m down-dip of the surface projection of mineralisation. The second-lowest pH for humus (by 0.01 pH units) is also 25 m down-dip of mineralisation.

Some of the geochemical results for line 6 are shown on Figure 47.4. The method that appears to show the most favourable response to mineralisation is Enzyme Leach^{SM}, although it is also the only selective leach data for B-Horizon that has yet been examined. A distinct high in Zn is noted 25 m south and down-dip of the surface projection of mineralisation. Twin-peak anomalies, 50 m north and south of mineralisation are also noted in Mn, Cu, and Ca by Enzyme Leach^{SM} and Mn shows a distinct depletion directly over mineralisation. In the case of Mn and Cu, the concentrations are higher in the down-dip direction of the deposit. The results for the same elements by Na-pyrophosphate are less pronounced and closer to mineralisation and in the case of Cu are inverse to those of Enzyme Leach^{SM}. The Na-pyrophosphate Cu trend in the humus is also closely correlated with ground surface elevation suggesting it responds more to surface effects than does the Enzyme Leach^{SM} data for the underlying clay. Many other elements have trends that are possibly related to mineralisation but have not yet been examined in detail. Data for additional selective leaches are available but have not yet been examined.

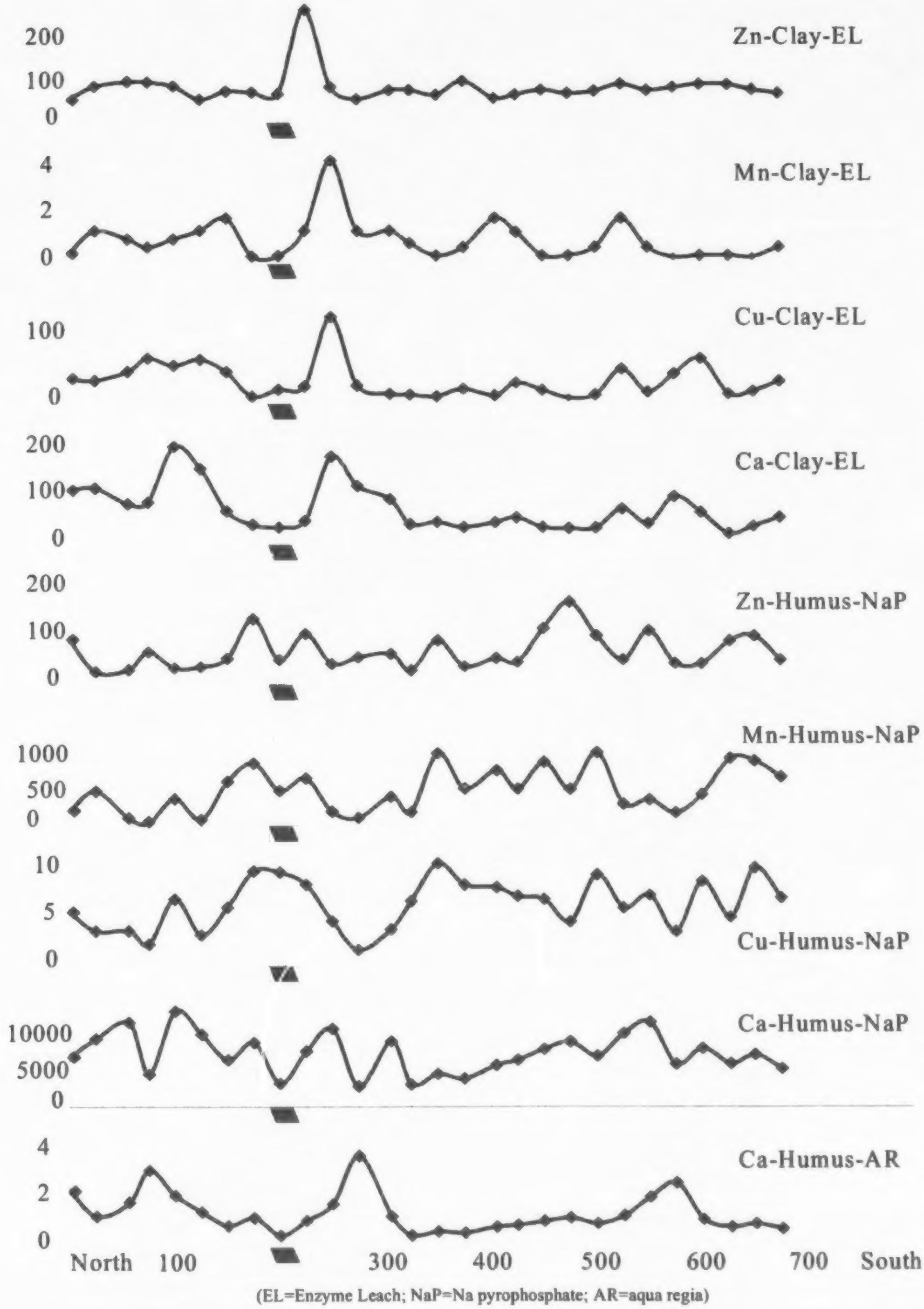
Forest Ring Sites

Forest rings are large circular features visible from the air in the boreal forest of Ontario, particularly in black spruce terrain. They are usually perfect circles (Figure 47.5) and are visible due to stunting or otherwise sparse vegetative growth around the rim of the circle and less often within the ring itself. They range in size from 50 m to almost 2 km across and their rims are usually about 20 m across. Several thousand have been documented across eastern Canada, mostly in Ontario (Veillette and Giroux 1999). The rings in Ontario typically occur in areas of thick overburden from the Abitibi clay-belt northward and westward.

Forest rings have been known for over 40 years and were originally thought to be biological features. The biological theory has recently been soundly disproved and a geological origin favoured (see Veillette and Giroux 1999 for a detailed account). However, until the work described herein, their true origin was not known.

The primary objective of this work was to test our hypothesis that the rings are centred on geological sources of negative charge and may be the visible manifestation of electrochemical cells. This, of course, has implications for mineral exploration in thick overburden because almost everything that explorationists seek is a potential source of negative charge including metallic mineralisation, kimberlites, oil and natural gas.

Since the fall of 1998, 8 rings have been investigated to at least the level of an orientation survey. The first orientation survey was carried out on 2 rings in the fall of 1998 with J. Veillette of the GSC to determine if: 1) the features are centred on sources of negative charge; and 2) if the physical depression noted at the edge of many of the rings is due to a carbonate depletion. It was reasonable to make this assumption since it is the surface of the underlying mineral soil that is depressed and since the rings occur almost exclusively in areas where the mineral soil is carbonate rich (Veillette and Giroux 1999). The results of that survey, carried out at the "Bean" ring, 60 km north-west of Hearst, (Figure 47.6) show strong carbonate depletion at the edge of the ring in the carbonate-rich clay till, coupled with a drop in the calcite/dolomite ratio. The latter suggests the depletion is due to acidification. This process is consistent with the electrochemical theory for ring development discussed below.



(EL=Enzyme Leach; NaP=Na pyrophosphate; AR=aqua regia)

Figure 47.4. Cross Lake, Line 6. Selected elements from humus and clay data sets. From a visual examination of these data and others, Enzyme Leach^{SM} seems to show the best response to mineralisation. Units are in ppm.

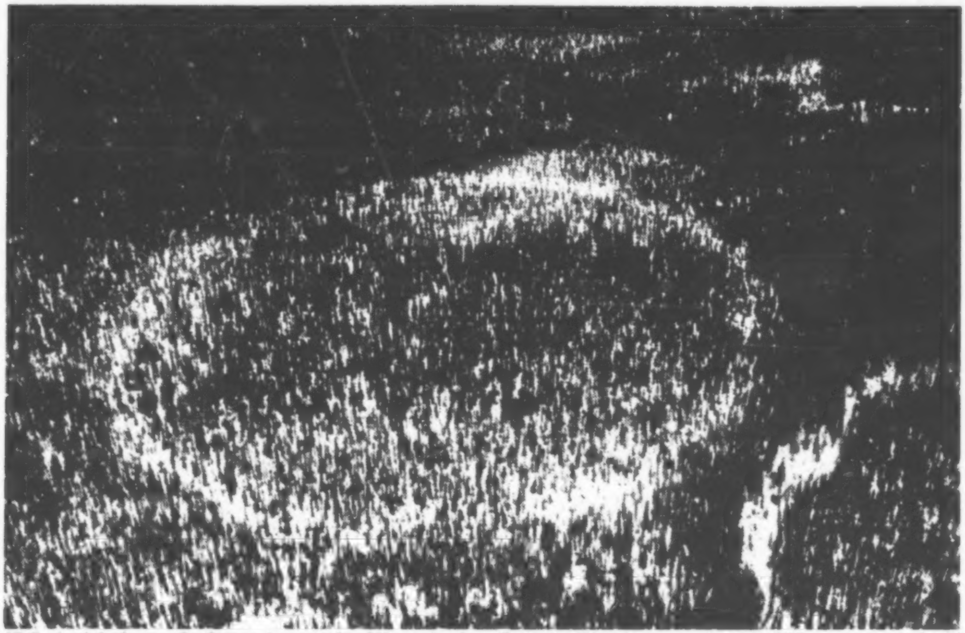


Figure 47.5. Aerial photo of a forest ring south of Kapuskasing, Ontario. Ring is approximately 300 m across and white areas are snow.

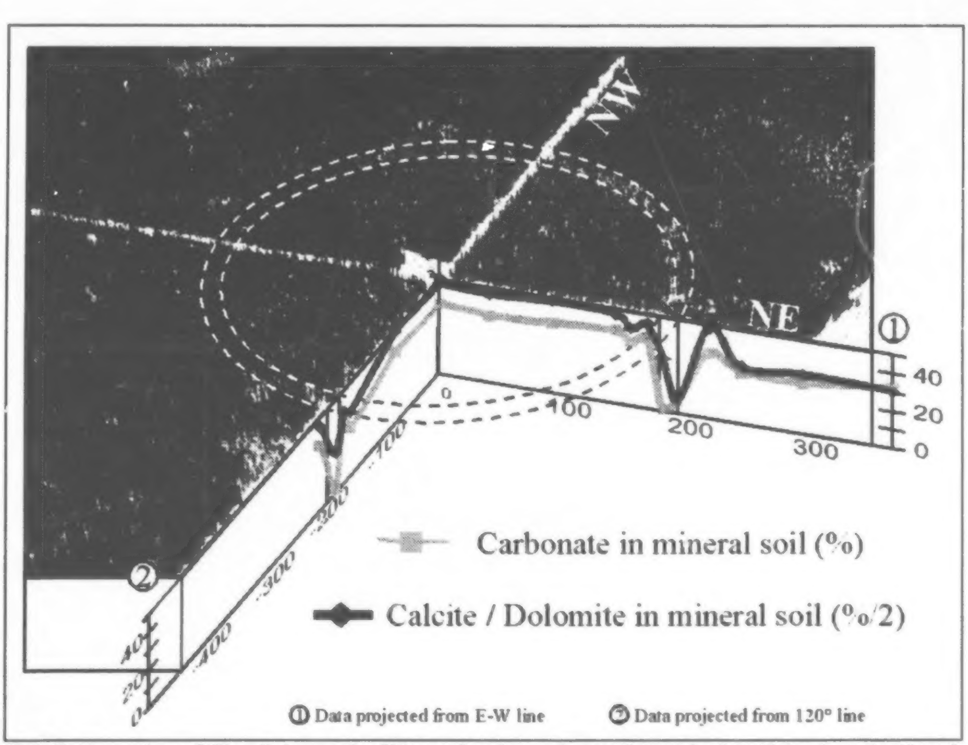


Figure 47.6. Cutaway view of "Bean" ring north of Hearst showing carbonate data and calcite/dolomite ratio. Note the strong depletion in both parameters at the ring edges.

Of the 8 rings visited, detailed subsurface work has been carried out on 3: the Bean ring and the Thorn-North and Thorn-South rings in Thorburn Township west of Timmins. Shallow auger holes were drilled in the winter of 1999 on the Bean and Thorn-South and in the winter of 2000 on Thorn-North. In addition, 3 holes were drilled several meters into bedrock at each of Thorn-North and Thorn-South and 1 hole into bedrock was drilled at the Bean ring.

Similar techniques were used to characterise the redox conditions as were used on the mineral deposit sites; in fact these techniques were first developed at the ring sites. Figure 47.7 shows down-hole SP, soil ORP on saturated peat and groundwater ORP. The down-hole SP and groundwater ORP show clear, chemically reduced areas within the centre of the rings, beginning at the edges. The ORP of saturated peat shows this too and also shows clear redox phenomena occurring at the boundary. This appears to be a near-surface expression of the redox reactions that are occurring at depth between reduced species in the ring and oxidised species outside.

Evidence of reduced areas within the rings has been noted on all 8 of the rings for which data were gathered. Figure 47.8 shows the soil-slurry ORP data collected during the augering program at Thorn-North. It shows a sharply reduced area beginning at the edges of the rings inward. This is most prominent on the west line at 1.5 m depth, the east line at 6 m depth and the north and south lines at 3 m depths. There are also complicating effects resulting from the juxtaposition of different media (sand and clay) because the ring transects the irregular western edge of an esker. The sand gives much higher background ORP and also affects the water level. The higher background may be real or it may be a measurement artefact resulting from using ORP probes on such radically different redox media. The differences in background are apparent on the south line centred on -150 m; the west line starting at 250 m and the east line starting at about 150 m.

The effect of the differing depth to the water table is apparent when comparing the redox signature on the west line with that on the east. The west line is in peat terrain and, despite the figure, the peat is saturated to surface (the well screens are at 8 m depth and therefore there must be a strong downward gradient in that area). The east line is in sand terrain and the water level is 4 m below ground surface. Samples taken from a depth of 1.5 m show a very strong redox response on the west rim of the ring but only a minor response on the east rim where the samples were taken 2.5 m above the water table. On the other hand, the rim on the east line shows a very good response at 6 m depth, which is the first set of samples on that part of the line that were collected below the water table.

Although this report is intended to summarise fieldwork, it is necessary to give a brief explanation of the theory of ring formation because it will not be immediately apparent to the reader why some of the data point to the presence of electrochemical cells under the rings. The theory (Hamilton 1998, Hamilton 2000a, 2000b) is that reduced features in bedrock consume oxidising agents in overburden that immediately overlies rock. This results in the development of strong (i.e., strong for earth materials) redox gradients between the reduced and the surrounding oxidised overburden, along which charge carrying species would migrate. The upward and outward migration of reduced species such as Fe^{2+} and HS^- would be coupled with inward migration of oxidised species such as UO_2^{2+} and dissolved oxygen radicals. Redox reactions that occur between these 2 groups are the mechanism that allows dissipation of negative charge away from the source. The theory of ring formation by this process is shown in Figure 47.9. As reduced metal ions such as Fe^{2+} oxidise at the rim of the ring, they precipitate as metal hydroxides and produce acid. Acid dissolves carbonate in the clay, ultimately causing the ground surface to drop. Increased soil moisture in these areas would cause stunted or at least different vegetation, resulting in a visible ring. This theory is consistent with the data from the Bean ring, which shows increased CO_2, temperature and iron in earth materials at the edge of the ring and decreased carbonate, pH and elevation of the clay surface. Data from the other rings have not yet been fully examined.

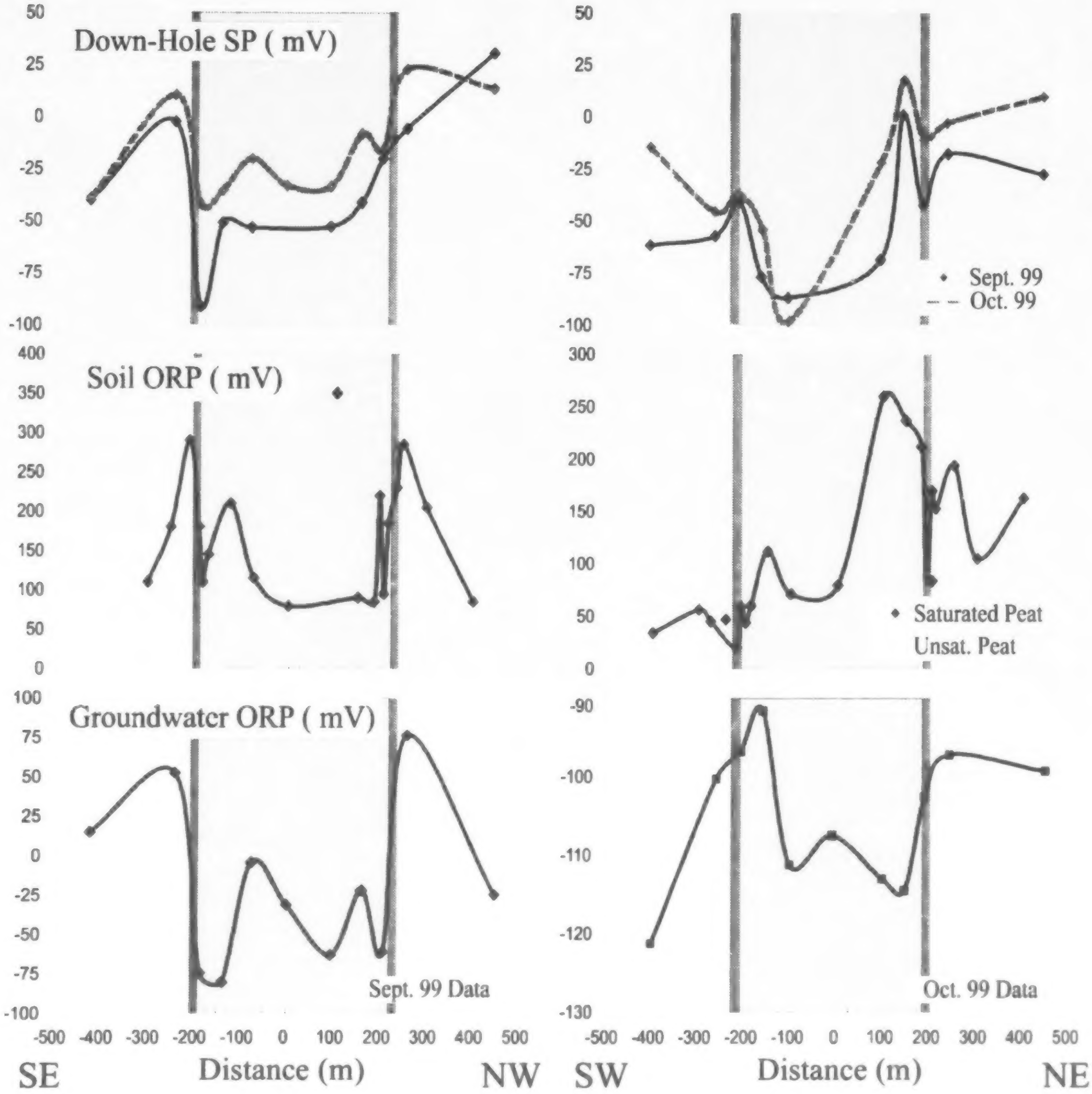


Figure 47.7. Down-hole SP, peat ORP, and groundwater ORP, at "Bean" ring, near Hearst, Ontario. Results show a strongly reduced area inside the ring relative to the outside.

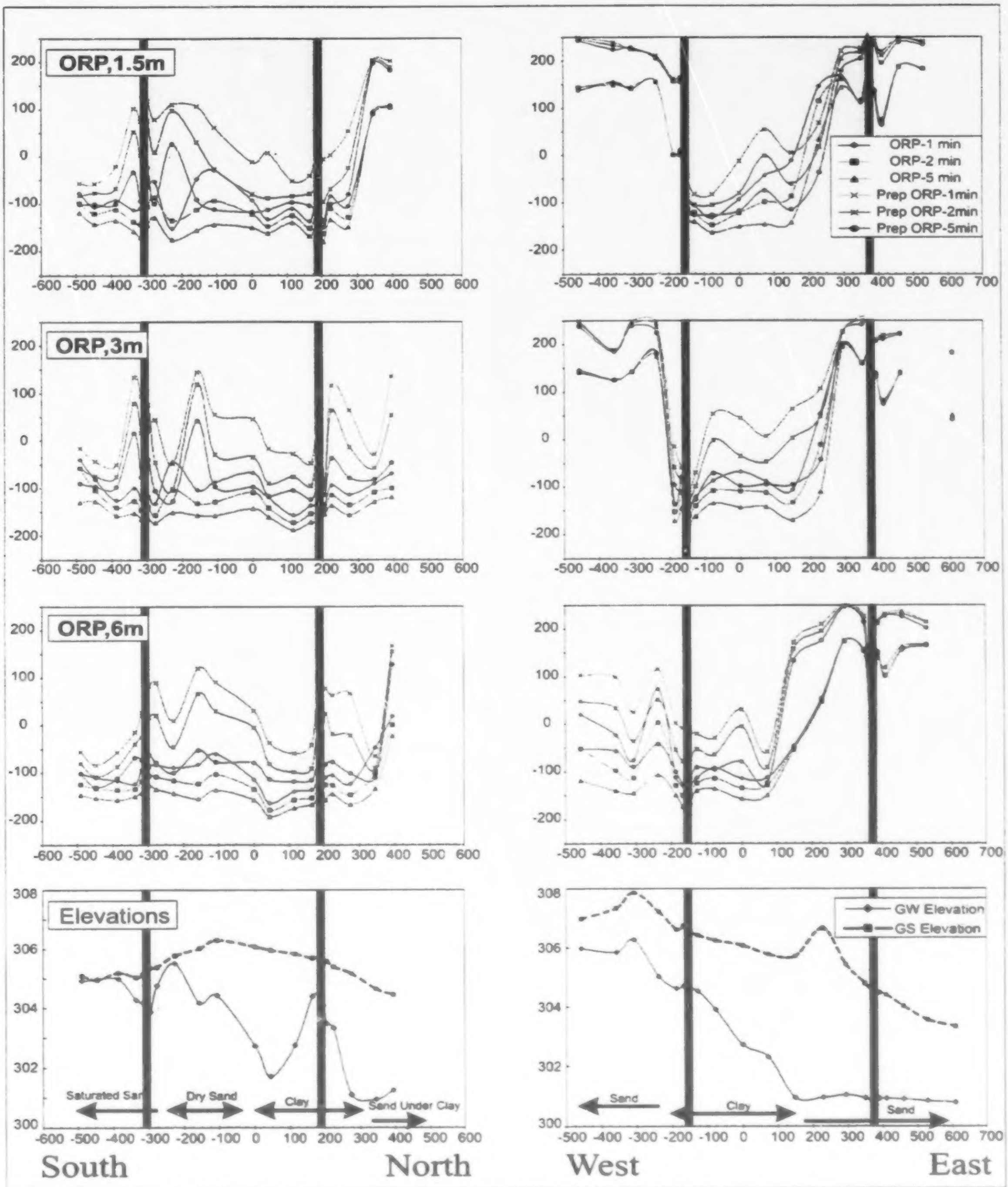
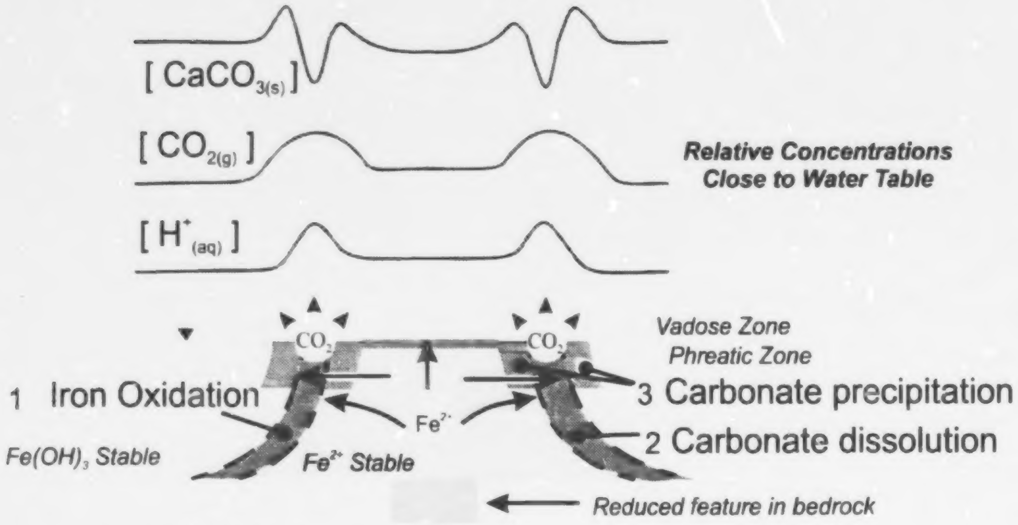


Figure 47.8. Down-hole ORP collected from split spoon samples in auger holes on 2 transects across the Thorn-North ring. Water levels and approximate overburden materials are shown in the bottom charts. Both the depth to water and the media type clearly affect the redox response obtained at the ring edges.



1 Iron Oxidation

$$Fe^{2+} + \tfrac{1}{2}O_2 + 2H_{2}0 \rightarrow Fe(OH)_3 + H^{+}$$

2 Carbonate dissolution

$$2H^{+}_{(aq)} + CaCO_{3(s)} \rightarrow Ca^{2+}_{(aq)} + H_2CO_{3(aq)}$$

3 Carbonate precipitation

$$H_2CO_{3(aq))} + Ca^{2+}_{(aq)} \rightarrow CaCO_{3(s)} + CO_{2(g)} + H_{2}0$$

Figure 47.9. Model for ring formation by electrochemical processes. Iron oxidation at the edges of the ring produces acid that dissolves carbonate and causes the ground surface to drop. The resulting increase in moisture in the rim alters the vegetation and results in a visible ring (from Hamilton, 2000b; modified after Hamilton 2000a)

The source of negative charge at the Bean ring has been determined to be natural gas. Fairly large quantities of gas are exsolving from solution and bubbling up from the shallow monitoring wells installed in the clay within the centre of the ring and sporadically outside the ring. Had there been buildings or businesses nearby there would be sufficient gas at this site to potentially act as property-scale resource. On the other hand, it would also be a serious danger to such structures since the methane is dissolved in shallow groundwater and would exsolve into foundation drainage systems, thereby being an explosion hazard.

The source of negative charge at Thorn-North and South is unknown despite 2 holes drilled to rock in the inside part of the rings at each site. On both sites, sericitized shear zones were encountered near the site centre. In the second hole at Thorn-North, a feldspar porphyry was encountered containing up to several percent pyrite with minor amounts of chalcopyrite. It is not known whether such small amounts of sulphide could result in the development of a reduced area over mineralisation. The site centre appears to rest on the contact between the porphyry and a gabbroic or diabase intrusion that, incidentally, contains almost 50 ppb combined platinum, palladium and gold.

Although the source of negative charge is not known on these 2 sites, it cannot be overburden sourced, as is the Bean ring. Both rings are transected by an esker in a flat clay-plain. Esker materials could not retain a gas, such as methane or H_2S. Furthermore, dry sand and moist clay are radically different redox media and the esker does not appear to affect the circularity of the ring at all. As such, this ring must have its source of negative charge in bedrock.

CONCLUSIONS

The outcome of the methods development studies has so far been the development of a number of techniques that are, albeit, problematic but that under the right conditions can quantitatively detect reduced zones in earth materials. The ability to do this is critical to our understanding of the processes that cause geochemical anomalies in deep burial environments. The work has also shown that chemically reduced areas over reduced geological features appear to be widespread, occurring on all the sites investigated so far.

The outcome of the studies over the Marsh Zone has been to show quite conclusively that, geochemistry can detect the presence of mineralisation through 20 m of fully saturated, unfractured glaciolacustrine clay. Preliminary examination of the data from the other mineral deposit sites suggests similar possibilities there too, despite overburden thicknesses exceeding 30 m. This may represent a first for geochemistry in thick, young glacial terrain. Once the principal component equations for various overburden types are established it may be possible to use these equations on other sites where the position of mineralisation is not known.

It is also clear from these results that the sample medium (e.g., sand vs. clay) and the terrain type (e.g., dry upland, or saturated peat terrain) has a bearing on the choice of selective leach technique. The tentative conclusion from the work presented so far is that Enzyme Leach^{SM} on B-horizon clay samples was more effective for dry areas than was Na-pyrophosphate on humus or aqua regia on either humus or B-Horizon. In moist peat terrain, Na-pyrophosphate on shallow peat samples showed better results than the other three methods. Data for additional selective leach procedures has not yet been examined.

The work over the forest-ring sites has been important both in the development of redox measuring techniques for earth materials and as an avenue of investigation in itself. Although previous theories as to the origin of these rings had already been disproved, this work is the first to demonstrate their true origin, i.e., as chemically reduced areas in overburden and, as such, the physical manifestation of electrochemical cells. All the rings investigated so far show significantly more negative redox conditions in overburden and groundwater within versus outside the ring. Almost all exploration targets are potential sources of negative charge including most forms of metallic mineralisation, kimberlites, oil, natural gas and coal. There are also many non-economic sources of negative charge in the earth. The only ring that has so far had its source of negative charge identified has a natural-gas source. The sources for the other 2 examined in detail are not known but evidence suggests they are in bedrock.

ACKNOWLEDGEMENTS

On the CAMIRO Sites, Marsh Zone and Cross Lake, a team of 4 including Eion Cameron, Beth McClenaghan, Stewart Hamilton and Brian Polk gathered the samples for chemical analysis. The analysis of these samples was funded by various partners of the CAMIRO group, who have waived the normal 2 year confidentiality period to allow the OGS to publish these results along with our electrochemical results. Eion Cameron, the CAMIRO team leader, and Beth McClenaghan, our colleague have collaborated on all aspects of the collection and interpretation of this data.

Many thanks go out to Kian Jensen of St. Andrew Goldfields, who hold the Marsh Zone property and to Ian Miller-Tait of Cross Lake Minerals. Both companies have kindly allowed us to work on their sites and been very forthcoming with the information we required to do our work.

The ring investigation has been aided at every stage by Bob Komarechka of Diatreme Explorations Incorporated. Diatreme completely funded access for drilling of the Bean and Thorn-South sites and made available a great deal of proprietary information on these and other rings. The early (and most important) stages of the ring investigation were carried out in partnership with Jean Veillette of the Geological Survey of Canada and his ideas lead directly to some of our further discoveries.

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48. Project Unit 00-029. Preliminary Impact Analysis of Operation Treasure Hunt Surveys

L.L. Churchill[1], J. Roque[1], C. Baker[2] and J.A. Fyon[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Government geological surveys provide pre-competitive, objective, regional-scale geoscientific data to help private sector effectively focus its exploration.

As part of the accountability framework for Operation Treasure Hunt (OTH), we are monitoring and documenting private sector economic activities triggered by OTH projects. In this article, we discuss the preliminary impacts of some OTH airborne geophysical and lake surficial geochemical surveys.

Accountability requires that government programs:

- Be accountable for public funds and demonstrate value for public investment
- Link project costs to results, and
- Manage effectively project-related information to ensure optimal program delivery and client service (Churchill and Fyon 1999).

ECONOMIC IMPACT AND RETURN ON PUBLIC INVESTMENT OF GOVERNMENT GEOSCIENCE PROGRAMS

Several studies document the immediate and long-term economic impact of geoscience information (Table 48.1). Maximum economic impact results when the geoscience data contribute to the discovery of a mine:

> **"Each $1 million spent through government geoscience projects will generate $5 million in exploration expenditures which will result in discoveries worth $125 million in situ. This in turn will generate 20 to 66 person years of exploration employment which will result in 80 person years of continuing employment, and include training for 5 students on-the-job, opportunities for Aboriginal Communities." (Ward 2000)**

FACTORS THAT INFLUENCE ECONOMIC IMPACT OF GEOSCIENCE DATA

In addition to the availability and quality of geological survey data, several other factors influence investment decisions by the exploration industry, including:

1. *Land Availability and Access to Land*
   In some areas where OTH surveys were conducted, much of the land is already staked or land is unable to be staked due to mineral right ownership defined in land tenure documents (e.g., patented

Table 48.1. Documented case studies illustrating the economic impact of publicly funded geological surveys. Abbreviations: MDA = Mineral Development Agreement.

TYPE OF STUDY/ACTIVITY	INFORMATION SOURCE	STUDY DATE	LEVERAGE OF PRIVATE SECTOR TO PUBLIC SECTOR INVESTMENT ($-PRIVATE SECTOR/ $-PUBLIC SECTOR)
Linkage between geoscience initiatives and exploration activity: Southern Baffin Island, Rankin Inlet, Victoria Island (NWT), Ungava (QC), Flin Flon	Neil Swan (Economist), Natural Resources Canada	1997	5:1 ($1557 million* to $155.7 million) (*The figure for 'exploration' includes development, so this number has been divided by 2 prior to calculating the leverage.)
Multi-disciplinary, integrated, collaborative project—development and testing of exploration methods & technology—EXTECH-II (Bathurst Mining Camp, New Brunswick)	D.M. Fraser Services Inc. for Geological Survey of Canada	1999	3.1:1 to 6.9:1 (minimum of $20 - $45 million exploration spending/$6.5 million geoscience investment)
Bedrock and mineral deposit mapping, geochemical mapping, geochronology Precambrian rocks, Canada–NWT Geoscience Mineral Development Initiative	Goss Gilroy Inc. (Management Consultants), for Department of Indian Affairs & Northern Development	1996	2:1 ($7.8 million public investment; minimum, short-term return only - 3yrs).
Airborne geophysical and geological surveys, South Australia Exploration Initiative (1992)	Centre for Resource Studies, Queen's University, Ontario.	1996	a) 5:1 (exploration); b) 25:1 (development); c) 250:1 (resource processing); d) tripling of exploration expenditures over 3 yr. period; e) 1 major discovery with a metal value exceeding the entire public investment. (based on public investment of $21.4 million).
Airborne geophysical surveys, New South Wales, Australia.	I. Lambert internal report, New South Wales Department of Mineral Resources.	1998	3 to 5:1 (public investment $25 million; minimum estimate based on increase in exploration expenditures only)
Surficial geochemical sampling: National Geochemical Reconnaissance Program (Geological Survey of Canada, 1973-1996).	Centre for Resource Studies, Queen's University, Ontario.	1996	37:1 ($1.55 billion public investment; minimum estimate, based on value of only 2 mineral discoveries)
Mapping applied to metallic mineral industry, Geological Survey of Canada activity.	Centre for Resource Studies, Queen's University, Ontario.	1996	82:1 (based on $1.3 billion public investment)

TYPE OF STUDY/ACTIVITY	INFORMATION SOURCE	STUDY DATE	LEVERAGE OF PRIVATE SECTOR TO PUBLIC SECTOR INVESTMENT ($-PRIVATE SECTOR/ $-PUBLIC SECTOR)
Surficial mapping, contamination potential mapping, aquifer mapping.	Impact of Geologic Mapping in Illinois, Illinois State Geological Survey, Circular C549	1991	27:1 (very conservative estimate based on 25% attribution of cost avoidance).
Geological survey work related to non-energy minerals.	Evaluating the Economic Rationale for Government Investment in Geoscience Information for Natural Resources Canada, M. Doggett, H. van Egteren, C. Findlay, J. Scoates	1985-1994	4:1 (private sector investment $8 billion in exploration expenditures to estimated $2 billion invested in geoscience by provincial and Federal governments)
Geoscience projects enhanced geoscience data base for province, British Columbia MDA	Final evaluation report for Canada-British Columbia Subsidiary Agreement on Mineral Development; Don Ference & Assoc Ltd.	1990	0.9:1 ($6 million in exploration activities initiated vs. government investment of $7 million)
23 multi-year geoscience projects contributing to development of a modern geoscientific database, Northwest Territories MDA	G. Nicholls, Dept. of Energy, Mines & Petroleum Resources, report on the Canada–Northwest Territories Economic Development Agreement's Geoscience Initiative	1994	3.4:1 (minimum of $24 million in exploration expenditures vs. $7 million government investment.)
Projects improving existing geological database, in particular geoscience mapping, Northwest Territories MDA	Goss Gilroy Inc. review of the Canada–Northwest Territories Economic Development Agreement's Mineral Initiatives	1995	1.9:1 (estimated minimum of $13 million private exploration expenditures resulting from government investment of $7 million)
Basic geoscientific information and mapping projects, Nova Scotia, New Brunswick MDA	D.W. Pollock & Assoc., Geological Survey of Canada, Open File Report 2498	1992	1.7:1 (estimated $56.4 million by private sector as follow-up government geoscience data released – government investment of $32.4 million)
Geoscience projects, i.e., new maps, structural studies, metallogenic maps and quaternary data, Newfoundland and Labrador MDA	Newfoundland Department of Mines and Energy, Open File Report NFLD/2254	1993	4.2:1 (estimated 90% of $155 million exploration expenditures triggered by government investment of $33.2 million)
Airborne Geophysics surveys, Victoria, Australia	N. Daws, unpublished presentation by Fugro Airborne Surveys to World Bank, multilateral aid sector.	2000	a) 9:1 (exploration); b) 64:1 (new mineral sands resources); c) 83:1 (new gold resources)

land). In remote areas, it is too costly for individual prospectors to stake or carry out exploration unless investors are committed to the exploration project prior to staking.

2. *Exploration Climate and Availability of Funds*
   World metal prices have been in decline for several years. Low metal prices mean companies seek ways to cut costs (i.e., decreased exploration). In addition, poor metal performance makes it difficult for companies to raise risk capital on stock exchanges. Both factors translate to fewer dollars available for mineral exploration.

3. *Awareness of OTH Data*
   The Ontario Geological Survey (OGS) promotes geoscience data, including those released under the OTH program, to help attract mineral exploration to Ontario. The OGS marketing instruments include:
   a) OTH website
   b) Ads in various media including *The Globe and Mail* and *The Northern Miner*
   c) Technical posters at major mineral conferences in Canada, and
   d) Press releases to announce the availability of OTH products. Notwithstanding these efforts, there are some international mineral explorationists that are not aware of OTH.

4. *Competition for Scarce Risk Capital*
   Much risk capital has flowed to new speculative investments in the digital economy, not the traditional minerals industry. In addition, some international investors still view Canada, and Ontario, in a negative light because of the Bre-X scandal.

5. *Timing of OTH Data Release*
   Much of the OTH geophysical and geochemical survey results were released between spring and early fall 2000. This is a time when exploration projects are in progress and budgets committed. Some OGS clients commented that they will acquire OTH data during the winter 2000, in advance of the 2001 exploration cycle. Impact of OTH projects should increase over the next year.

GEOSCIENCE ECONOMIC IMPACT MEASURES

The OGS monitors several metrics to measure the performance of the OTH airborne geophysical and surficial geochemical survey products.

1. Level of private sector exploration activity triggered by the OTH surveys
   - OTH product sales
   - claims staked
   - client interactions with OGS staff
   - assessment reports filed for OTH survey areas
   - exploration expenditures
   - discoveries of economic mineral deposits

2. Client survey/questionnaires
   - measure, in part, client satisfaction with OTH products
   - determine the degree to which OTH products influence a prospecting or mineral exploration decision

The following is a preliminary assessment of some of the tracking metrics for the OTH Airborne Geophysical surveys.

Product Sales

Approximately 3200 airborne geophysical product units were sold between July and September 2000. These product sales are a direct measure of immediate client interest in OTH airborne geophysical products. That client interest is a required precursor to staking, guided by the new OTH data.

OTH Airborne Geophysical Survey Area	Publication Release Date	# of 1:20 000 map sheets per survey	Total Unit Sales as of September 20, 2000	# of Geophysical CD-ROMS per survey	Total Unit Sales as of September 20, 2000
Cochrane	July 20, 2000	7	238	6	26
Vickers	July 20, 2000	5	185	2	11
Temagami–Cobalt	July 27, 2000	5	214	4	16
Schreiber	August 3, 2000	11	387	6	46
Kirkland Lake	August 17, 2000	19	376	4	19
Garden–Obonga	August 31, 2000	28	1277	4	21
Matheson	September 13, 2000	9	399	4	15
TOTAL SALES			**3076**		**154**

Claim Staking Activity

Staking claims follows from sales of OTH geological products. There are many factors that contribute to the staking of claims in a given geographic area including new geologic information becoming available, i.e., OTH geophysical surveys, OTH surficial geochemical surveys, exploration activity related to palladium-platinum exploration. Claim staking for several OTH airborne geophysical survey areas reveals several patterns (Figures 48.1, 48.2, 48.3, 48.4, 48.5, 48.6, 48.7 and 48.8), attributed partly to the release of both the airborne geophysical survey data and the surficial geochemical data:

- claim units (1 claim unit = 16 ha) in good standing have increased in the Temagami, Garden–Obonga and Schreiber airborne geophysical survey areas since March 2000 (Figures 48.1, 48.2, 48.3); surficial geochemical survey data were released for parts of the Garden–Obonga and Schreiber
- the number of net new claim units (newly recorded claims less cancelled claims) held in the Kirkland Lake survey area turned positive for the first time since April 1998 (Figure 48.4) and increased by 1200 units in the Schreiber area in April 2000 (Figure 48.5)
- In the Schreiber, Garden–Obonga and Kirkland Lake airborne geophysical survey areas, the staking of new claims exceeds historic staking patterns prior to the release of OTH data. The number of new claim units staked increased by two to five times compared to the previous high over the last 2 years. This dramatic increase in the number of claim units staked for the Schreiber and Garden–Obonga areas is coincident with a number of triggers, including accelerated exploration activity related to palladium and platinum, a recently announced expansion of the Lac des Iles Mine, and release of OTH airborne geophysical and surficial geochemical products (Figures 48.6, 48.7 and 48.8).

The staking patterns suggest the positive impact of the OTH airborne geophysical and OTH and core surficial geochemical surveys. Staking is the first step leading to exploration expenditures.

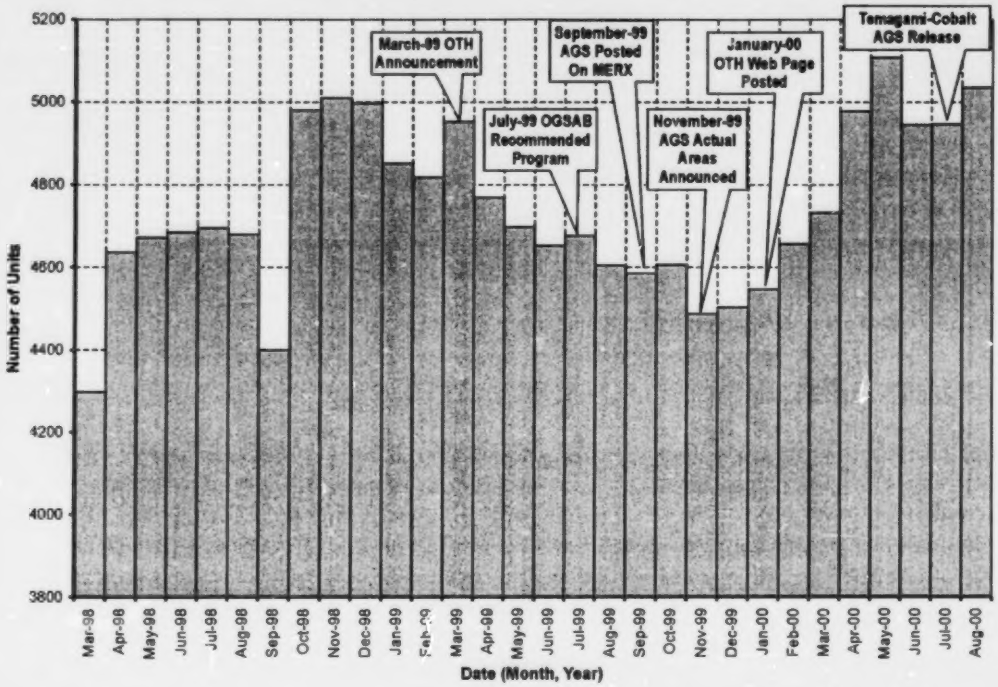

Figure 48.1. Active claim units in the Operation Treasure Hunt (OTH) Temagami–Cobalt Airborne Geophysical Survey (AGS) area. Abbreviations: OGSAB = Ontario Geological Survey Advisory Board.

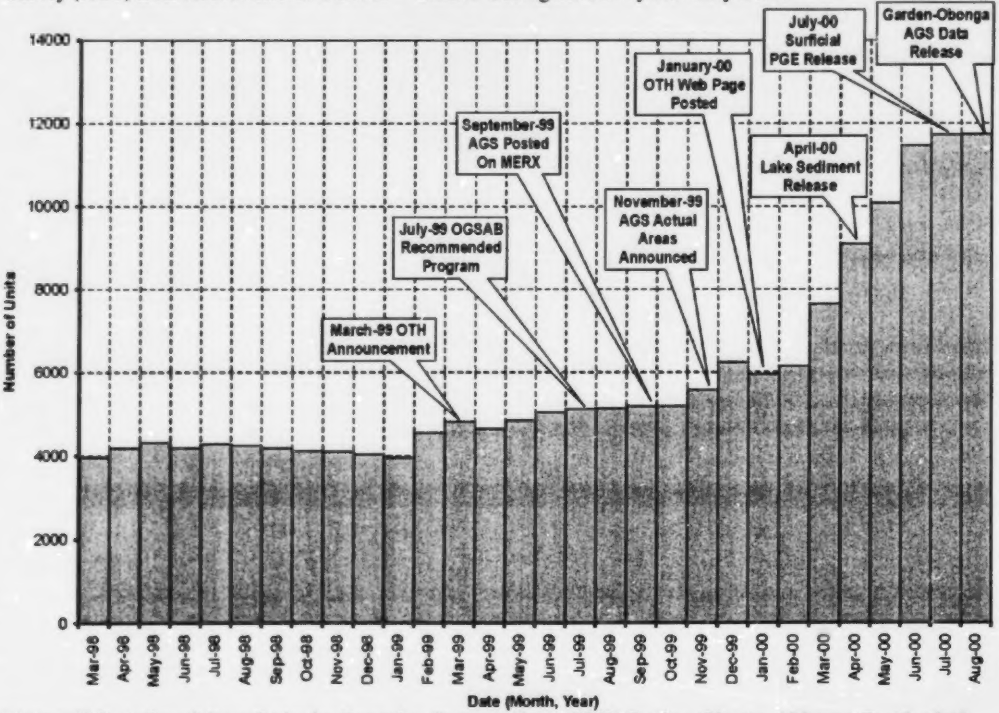

Figure 48.2. Active claim units in the Operation Treasure Hunt (OTH) Garden–Obonga Airborne Geophysical Survey (AGS) area. Abbreviations: PGE = platinum group elements; OGSAB = Ontario Geological Survey Advisory Board.

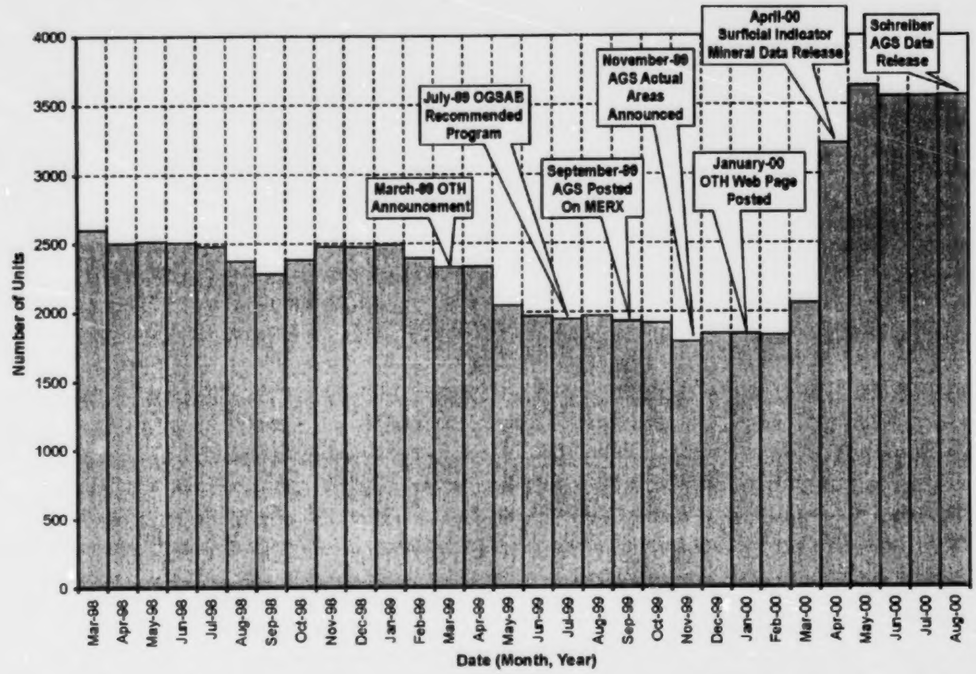

Figure 48.3. Active claim units in the Operation Treasure Hunt (OTH) Schreiber Airborne Geophysical Survey (AGS) area. Abbreviations: OGSAB = Ontario Geological Survey Advisory Board.

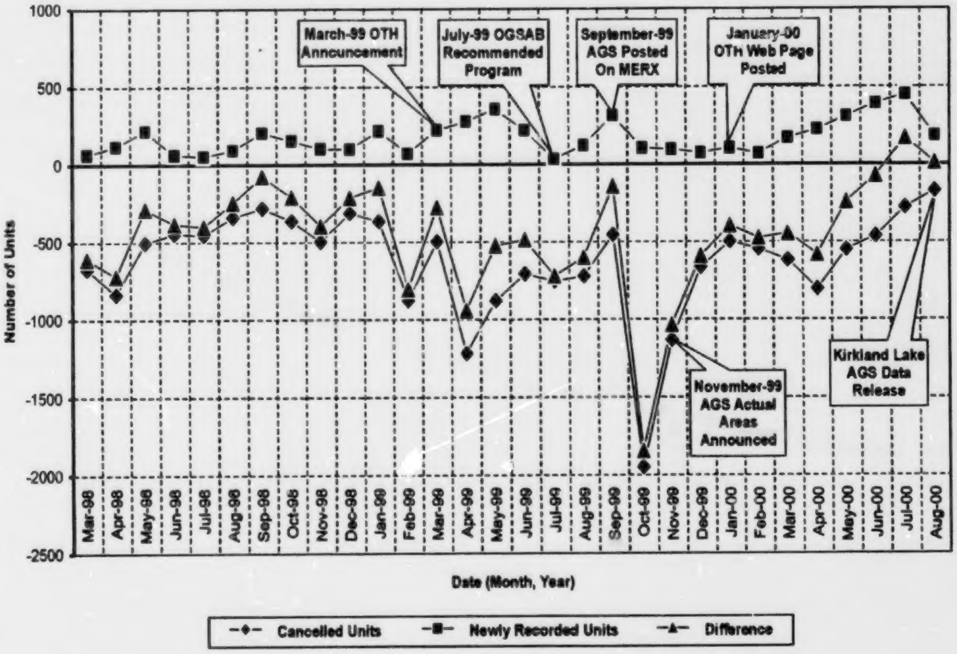

Figure 48.4. Newly recorded and cancelled claim units in the Operation Treasure Hunt (OTH) Kirkland Lake Airborne Geophysical Survey (AGS) area. Abbreviations: OGSAB = Ontario Geological Survey Advisory Board.

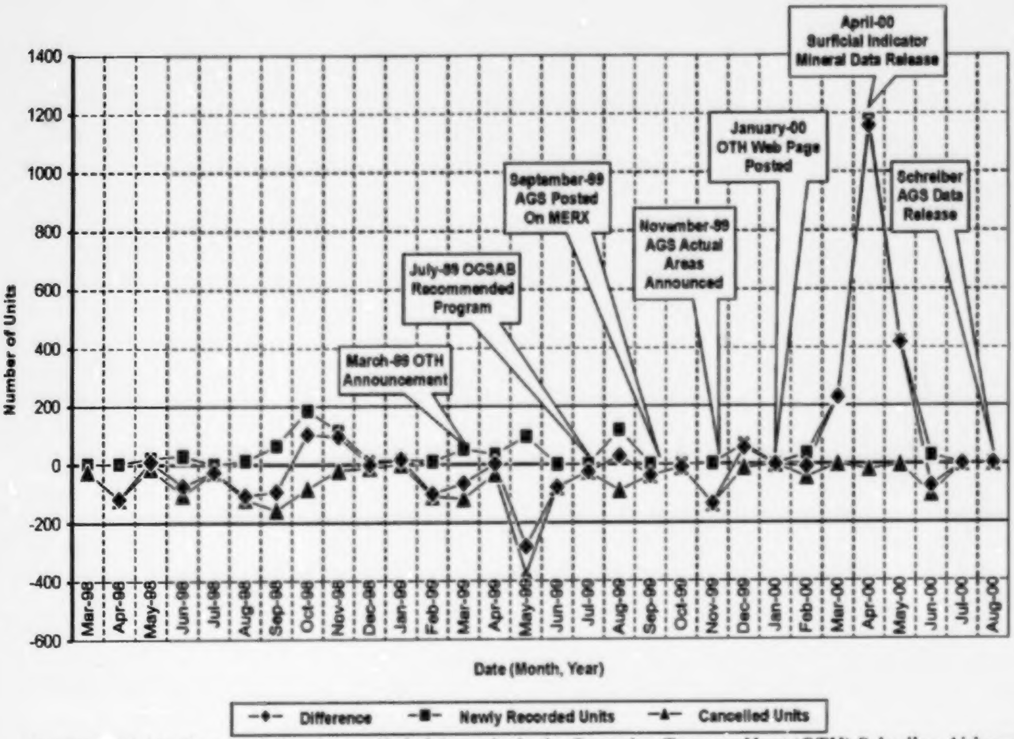

Figure 48.5. Newly recorded and cancelled claim units in the Operation Treasure Hunt (OTH) Schreiber Airborne Geophysical Survey (AGS) area. Abbreviations: OGSAB = Ontario Geological Survey Advisory Board.

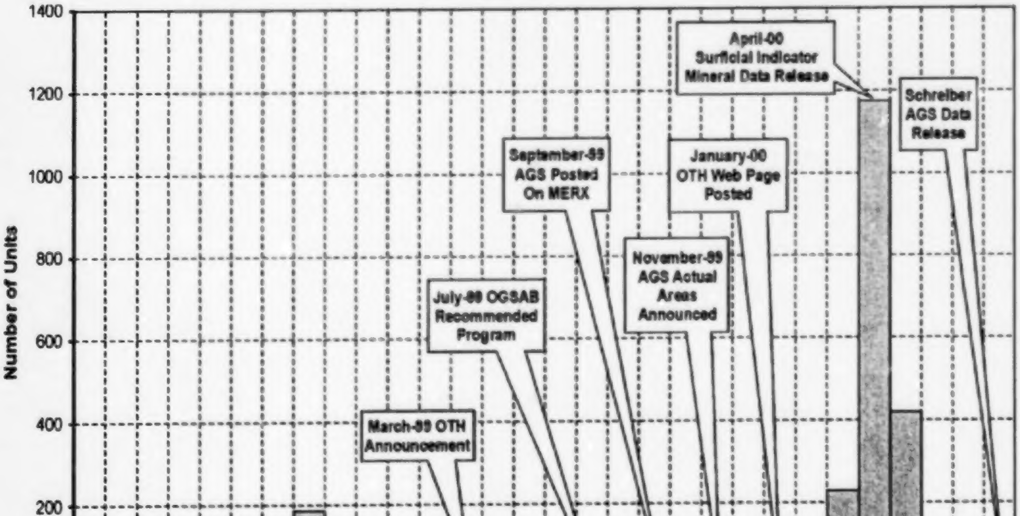

Figure 48.6. Newly recorded claim units in the Operation Treasure Hunt (OTH) Schreiber Airborne Geophysical Survey (AGS) area. Abbreviations: OGSAB = Ontario Geological Survey Advisory Board.

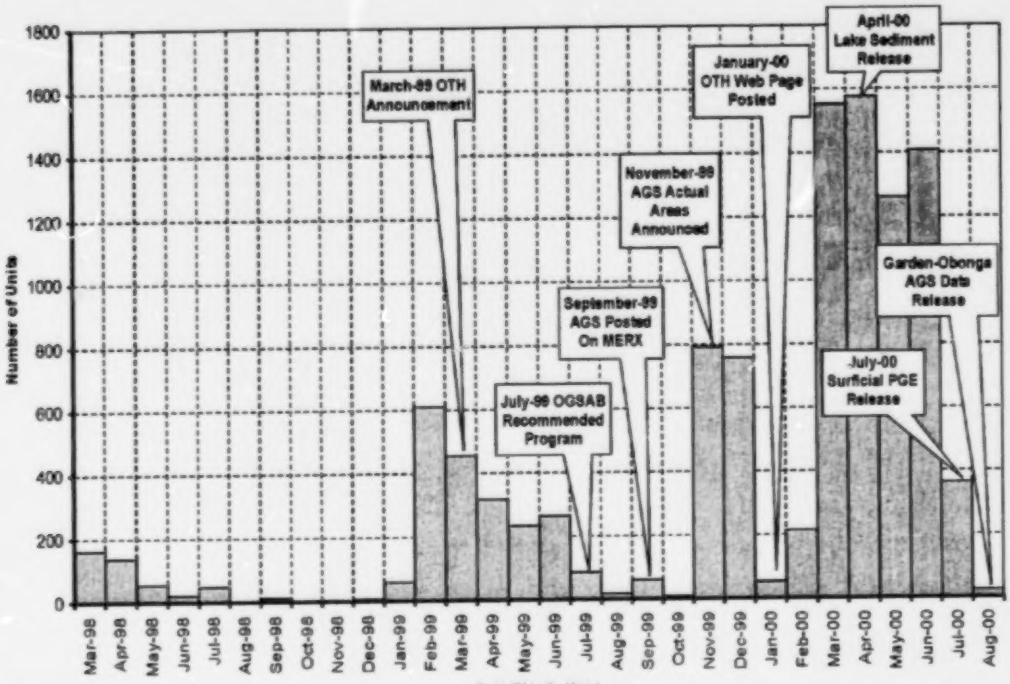

Figure 48.7. Newly recorded claim units in the Operation Treasure Hunt (OTH) Garden–Obonga Airborne Geophysical Survey (AGS) area. Abbreviations: PGE = platinum group elements; OGSAB = Ontario Geological Survey Advisory Board.

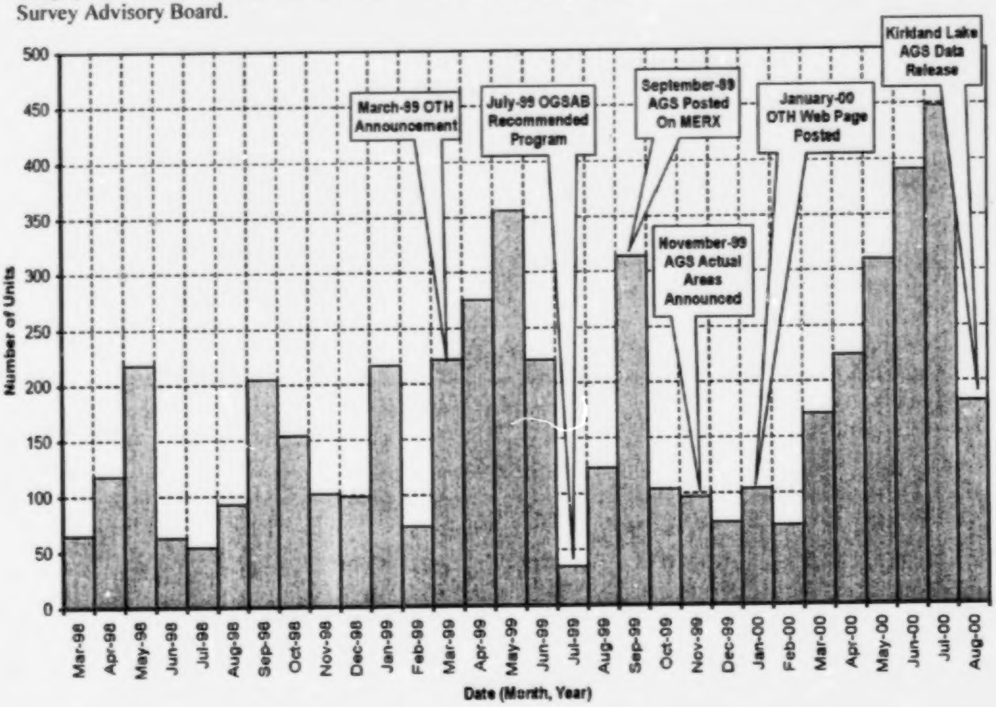

Figure 48.8. Newly recorded claim units in the Operation Treasure Hunt (OTH) Kirkland Lake Airborne Geophysical Survey (AGS) area. Abbreviations: OGSAB = Ontario Geological Survey Advisory Board.

Investment Decisions

In the next phase of this study, claim holders will be canvassed to determine the extent to which the OTH surveys were responsible for their prospecting and exploration expenditures and the amount of the expenditures or benefits of option agreements.

The OGS will utilize a questionnaire to seek information about:

- investment decisions by minerals sector clients carrying out activities in OTH survey areas
- benefits to consultants and the minerals service sector, attributed to the OTH survey data. As a result of OTH surveys, secondary markets are emerging that create jobs in the service industry to enhance the OTH airborne geophysical and surficial geochemical products
- jobs created as a direct result of work carried out to prospect or explore ground acquired because of the OTH airborne geophysical and surficial geochemical survey data

To acquire meaningful information from the questionnaire, clients may be asked to provide sensitive or confidential information. The co-operation and trust of the mineral industry are critical. The OGS will use the data gathered through the questionnaire in aggregate to demonstrate the impacts of the OTH projects.

WILL OTH INVESTMENT STIMULATE MINERAL EXPLORATION ACTIVITY AND INVESTMENT IN ONTARIO?

Clients are staking ground in areas where Operation Treasure Hunt surveys have been conducted and data released. However, it is premature to quantify the magnitude of prospecting and exploration expenditures. The OGS will continue to monitor, over the long-term, the magnitude of exploration expenditures attributed to OTH projects.

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Index of Authors (with corresponding article numbers)

A

Ahmad, S., 27
Allan, S.E., 34
Armstrong, D.K., 39
Arnold, J., 21
Ayer, J.A., 3, 7, 10, 11

B

Bailes, A.H., 13
Baker, C.L., 40
Barnett, P.J., 38
Beakhouse, G.P., 19, 20, 21
Becker, J.K., 9
Benn, K., 9, 12
Berdusco, B.J., 14
Berger, B., 8, 31
Breaks, F.W., 24
Boast, M., 30

C

Churchill, L.L., 40, 48
Corkery, M.T., 13
Cranston, D.R., 47

D

Debicki, R., 31
Denomme, R., 40
Deschamps, S., 43
DeWolfe, J.C., 25
Dinel, É., 12
Dubé, B., 13
Dyer, R., 40, 44, 45, 46

E

Easton, R.M., 28

F

Fowler, A.D., 7, 11
Fyon, J.A., 1, 40, 41, 48

G

Gao, G., 32
Gibson, H.L., 11

H

Hall, R.P., 6
Hallé, J., 15, 16
Hamilton, S.M., 47
Harris, J.R., 13
Hart, T.R., 17, 18
Houlé, M., 11
Hrominchuk, J.L., 29
Hughes, D.J., 6

J

Jackson, J.E., 36
James, R., 21
Johns, G.W., 6, 7

K

Kelley, S.P., 24
Kelly, R., 40

L

Lafrance, B., 25
Lalonde, A.E., 8
Leblanc, G., 7
Lesher, C.M., 10, 11
Luinstra, B., 5

M

MacDonald, C.A., 17, 18
Madon, Z., 40, 41
McNicoll, V., 13
Merlino, G., 40
Morris, T.F., 33
Mueller, E., 41
Murphy, A.J., 30

O

O'Connor, J.P., 30
Oliver, H.S., 6

P

Panagapko, D., 13
Parker, J.R., 13, 22, 23
Percival, J.A., 13
Pigeon, L., 8

R

Reford, S.W., 40, 41
Rogers, N., 13
Romer, R.L., 24
Roque, J., 48
Rowell, D., 32
Russell, D.F., 37

S

Santaguida, F., 40, 42
Sanborn-Barrie, M., 13
Scott, R.G., 30
Schwerdtner, W.M., 27
Searcy, C.A., 35
Singhroy, V.H., 38
Skulski, T., 13
Smith, S.R., 24
Spray, J.G., 30
Sproule, R.A., 10, 11
Stone, D., 13, 15, 16
Stott, G.M., 13, 14, 25
Straub, K.H., 26

T

Thurston, P.C., 2, 10, 11, 13, 40
Tindle, A.G., 24
Tomlinson, K.Y., 13
Tuchscherer, M., 30

V

Vaillancourt, C., 4

W

Whalen, J.B., 13

Y

Young, M.D., 13

Metric Conversion Table

Conversion from SI to Imperial			Conversion from imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
LENGTH					
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
AREA					
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
MASS					
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.